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Energy Use Patterns and Environmental Implications of Direct-Fired Industrial Processes

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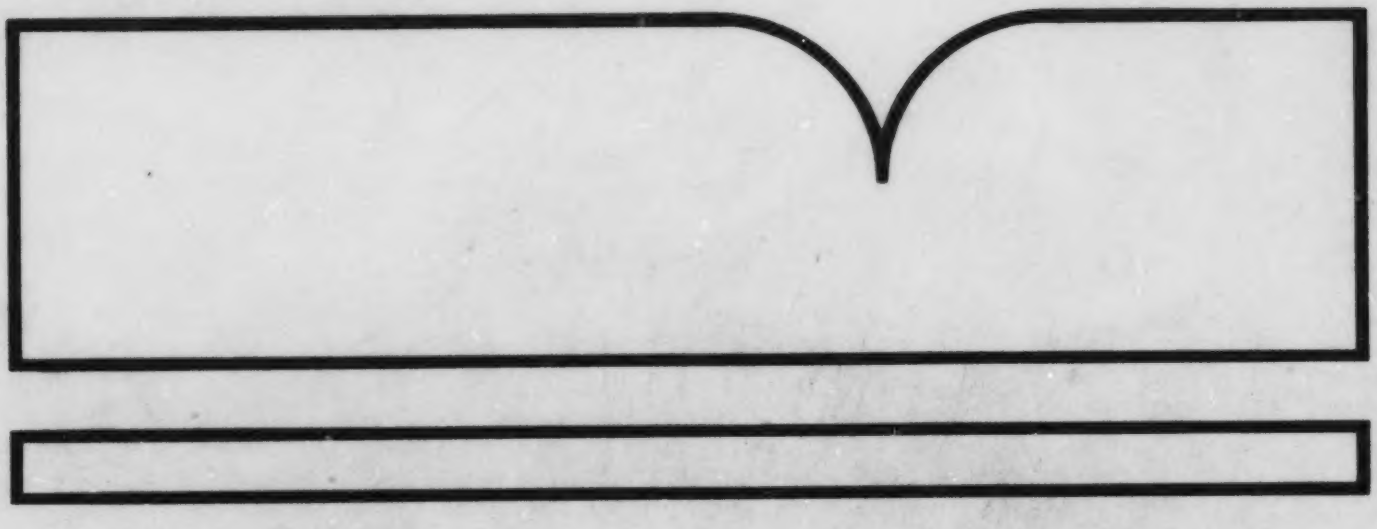

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ENERGY USE PATTERNS AND ENVIRONMENTAL IMPLICATIONS OF DIRECT-FIRED INDUSTRIAL PROCESSES

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16. ABSTRACT

Energy consumption patterns and environmental impacts of direct-fired processes in the industrial sector were identified. The potential effects of fuel switching in several of these processes were determined. An extensive bibliography lists the sources consulted in this study.

Annual energy consumption in the United States has totalled approximately 75 quads (1 quad = 10^{15} Btu) in recent years. Direct-fired processes in the industrial sector consume 10 percent of this energy, or seven quads per year. Most of the direct-fired energy consumption occurs in the manufacture of chemicals, petroleum products, primary metals, and mineral products (cement, glass, brick, etc.).

An estimated 60 percent of all direct-fired fuel is burned in processes whose only emissions are products of combustion. However, the more important environmental impacts are associated with the firing of the remaining 40 percent of the fuel. This energy is consumed in processes that co-mingle combustion gases with materials being processed. These materials include volatile metals from blast furnaces, dust from cement kilns, and fine particulate from glass furnaces.

Switching of some direct-fired processes to coal has been proven feasible. Fuel switching would have a more pronounced environmental impact on those processes emitting only products of combustion.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Metal Industry	Air Pollution	Direct-Fired Process	
Chemical Industry	Energy	Direct Firing	
Petroleum Refinery	Fossil Fuels	Direct-Fired Equipment	
Paper Industry	Combustion	Industrial Energy Consumption	
Glass Industry	Equipment		
Food Industry	Fuel Consumption		
Furnaces			

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory--Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report documents the identification of those industrial direct-fired processes in the United States which are major energy consumers. The report tabulates the energy consumed by these processes and describes the environmental residuals generated by each. In addition, it indicates which processes are likely to be modified or to undergo fuel-substitution in the near future, and what the environmental consequences of such changes might be. This study has created an energy data base to be used in assessing the relative importance of individual direct-fired processes to industrial energy-use environmental impacts. It will be useful to those who need to know the environmental significance of these processes, whether it be for developing regulations, determining future research program needs, or identifying processes with minimal environmental impacts. Further information on energy use patterns and thier environmental implications may be obtained from the Alternate Energy Sources Branch of the Energy Pollution Control Division, IERL-Ci.

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Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

Energy consumption patterns and environmental impacts of direct-fired processes in the industrial section were identified. The potential effects of fuel switching in several of these processes were determined.

Annual energy consumption in the United states has totalled approximately 75 quads (1 quad = 10^{15} Btu) in recent years. Direct-fired processes in the industrial section consume 10 percent of this energy, or seven quads per year. Most of the direct fired energy consumption occurs in the manufacture of chemicals, petroleum products, primary metals, and mineral products (cement, glass, brick, etc.). Twenty-seven individual processes in these four industry groups consume 60 percent of all direct-fired energy.

An estimated 60 percent of all direct-fired fuel is burned in processes whose only emissions are products of combustion. However, the more important environmental impacts are associated with the firing of the remaining 40 percent of the fuel. This energy is consumed in processes that co-mingle combustion gases with materials being processed. These materials include volatile metals from blast furnaces, dust from cement kilns, and fine particulate from glass furnaces.

Switching of some direct-fired processes, e.g., calcining the raw materials in cement kilns, to coal has been proven feasible. The use of coal-based fuel in many other processes appears unlikely, however. Fuel switching would have a more pronounced environmental impact on those processes emitting only products of combustion. Those processes that co-mingle combustion gases with process material would be comparatively less affected by fuel switching.

This report was submitted in partial fulfillment of Contract No. 68-01-4136 by Radion Corporation under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from June 15, 1979 to December 19, 1979, and work was completed on August 13, 1980.

CONTENTS

Section		Page
	DISCLAIMER.	ii
	FOREWORD.	iii
	ABSTRACT.	iv
	TABLES.	vii
	FIGURES	ix
	SUMMARY	x
1.0	INTRODUCTION.	1
	1.1 Objective.	1
	1.2 Background	1
	1.3 Approach	2
2.0	ENERGY CONSUMPTION PROFILE.	6
	2.1 Industrial Energy Consumption.	6
	2.2 Industrial Manufacturing Direct-Fired Energy Consumption.	12
3.0	POLLUTION POTENTIAL PROFILE	22
	3.1 Major Processes.	22
	3.1.1 Petroleum Refining/Chemicals.	23
	3.1.2 Iron and Steel.	25
	3.1.3 Mineral Processing.	28
	3.1.4 Primary Nonferrous Metals	29

CONTENTS (continued)

Section		Page
	3.2 Minor Processes.	30
	3.2.1 Chemicals	30
	3.2.2 Petroleum Refining.	31
	3.2.3 Mineral Processing.	31
	3.2.4 Primary Metals (Ferrous and Nonferrous)	32
	3.2.5 Food and Paper.	32
4.0	CONCLUSIONS AND DATA NEEDS.	33
	4.1 Conclusions.	33
	4.1.1 Energy Consumption Profile Analysis	33
	4.1.2 Pollution Potential Profile Analysis.	34
	4.2 Data Needs	36
	4.2.1 Energy Consumption Profile Analysis	36
	4.2.2 Pollution Potential Profile Analysis.	37
	4.2.3 General Data Needs.	38
	APPENDIX A - Detailed Energy Consumption Data for Six Major Industries	39
	APPENDIX B - Methodology.	55
	REFERENCES	67

TABLES

Table No.		Page
1	Industrial Manufacturing Energy Consumption, 10^{12} Btu/yr. .	xiv
2	Fuel Use and Purchased Electricity for the Six Major Manufacturing Industry Groups in 1977, 10^{12} Btu/yr.	xv
3	Comparison of Manufacturing Direct-Fired Energy Consumption Estimates, 10^{12} Btu/yr	xvii
4	Major Direct-Fired Processes, by Industry	xvii
5	Summary of Major Energy Consuming Direct-Fired Processes. .	xviii
6	Composition of Direct-Fired Fuel, by Industry Group	xix
7	Basic Raw Materials for United States Manufacturing Industries.	3
8	Total Energy Consumption in U.S. - 1974	7
9	Industrial Energy Consumption, 10^{12} Btu/yr.	8
10	Industrial Manufacturing Energy Consumption, 10^{12} Btu/yr. .	9
11	Input Energy of the Six Major Manufacturing Industry Groups, 10^{12} Btu/yr	11
12	End Use of Fuel in the Industrial Manufacturing Sector, % .	13

TABLES (Continued)

Table No.		Page
13	Fuel Use and Purchased Electricity for the Six Major Manufacturing Industry Groups, 10^{12} Btu/yr.	14
14	Summary of Process Energy Analysis for Six Major Industry Groups, 10^{12} Btu/yr	16
15	Summary of Major Process- or Product-Related Energy Consumptions, 10^{12} Btu/yr	20
16	Summary of Major Energy Consuming Direct Fired Processes. . .	21

FIGURES

Figure No.		Page
1	Total Energy Consumption in U.S. - 1974.	xi
2	U.S. Industrial Energy Consumption	xii
3	End-Use of Fuel in Manufacturing Industries	xiii

SUMMARY

Although there has been considerable study of industrial energy consumption in recent years, there has been no investigation prior to this one which attempted to characterize the population of industrial processes which are direct-fired.* Because of the need for better understanding of this class of processes, this project was conducted and used as a basis for examination of the energy consumption trends and environmental consequences associated with direct-fired systems.

The relative importance of industrial energy use is shown in Figure 1, which indicates total U.S. consumption by all major sectors. The importance of manufacturing in total industrial energy consumption is shown by Figure 2. The distribution of energy use within manufacturing is shown in Figure 3. Direct-fired processes account for about 30 percent of total manufacturing energy consumption and are mostly found in a few industries. The most energy-intensive 2-digit Standard Industrial Classification (SIC) industry groups are shown in Table 1 with total consumption for the years 1971 and 1977. From these data it appears that use of energy in manufacturing has remained about constant in recent years except in the chemical industry group where there has been a significant increase. The distribution between industry groups and type of use is presented in Table 2 which shows almost all direct-fired fuel being used in four types of activity: petroleum refining, production of chemicals, production of metals, and processing of minerals.

After the data required to put the energy consumed in direct-fired processes into perspective was collected, the process analysis was carried

*Direct-fired processes are those which burn fossil-based fuels to supply thermal energy from the flame and/or products of combustion. Steam generation is not included in this category for the purposes of this study.

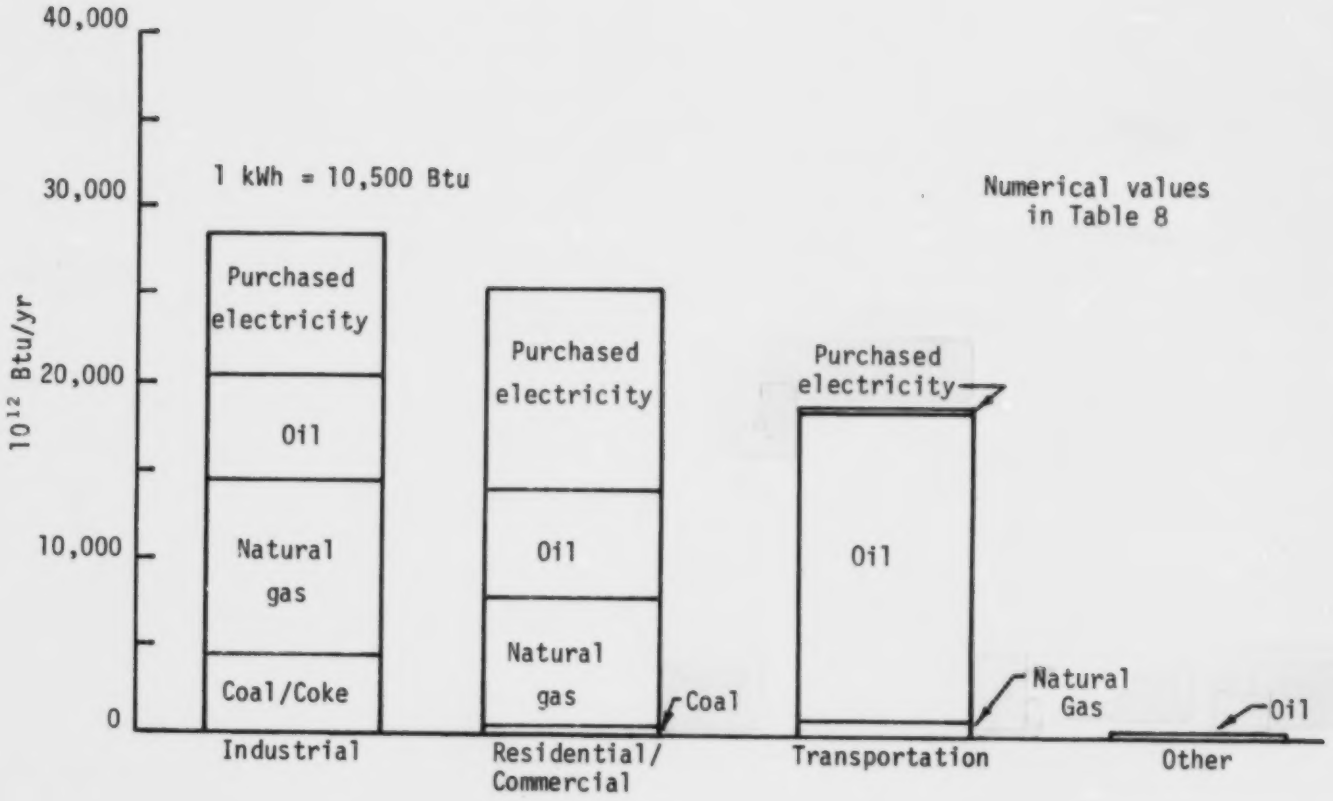

Figure 1. Total energy consumption in U.S. - 1974.

Source: U.S. Department of the Interior (1)

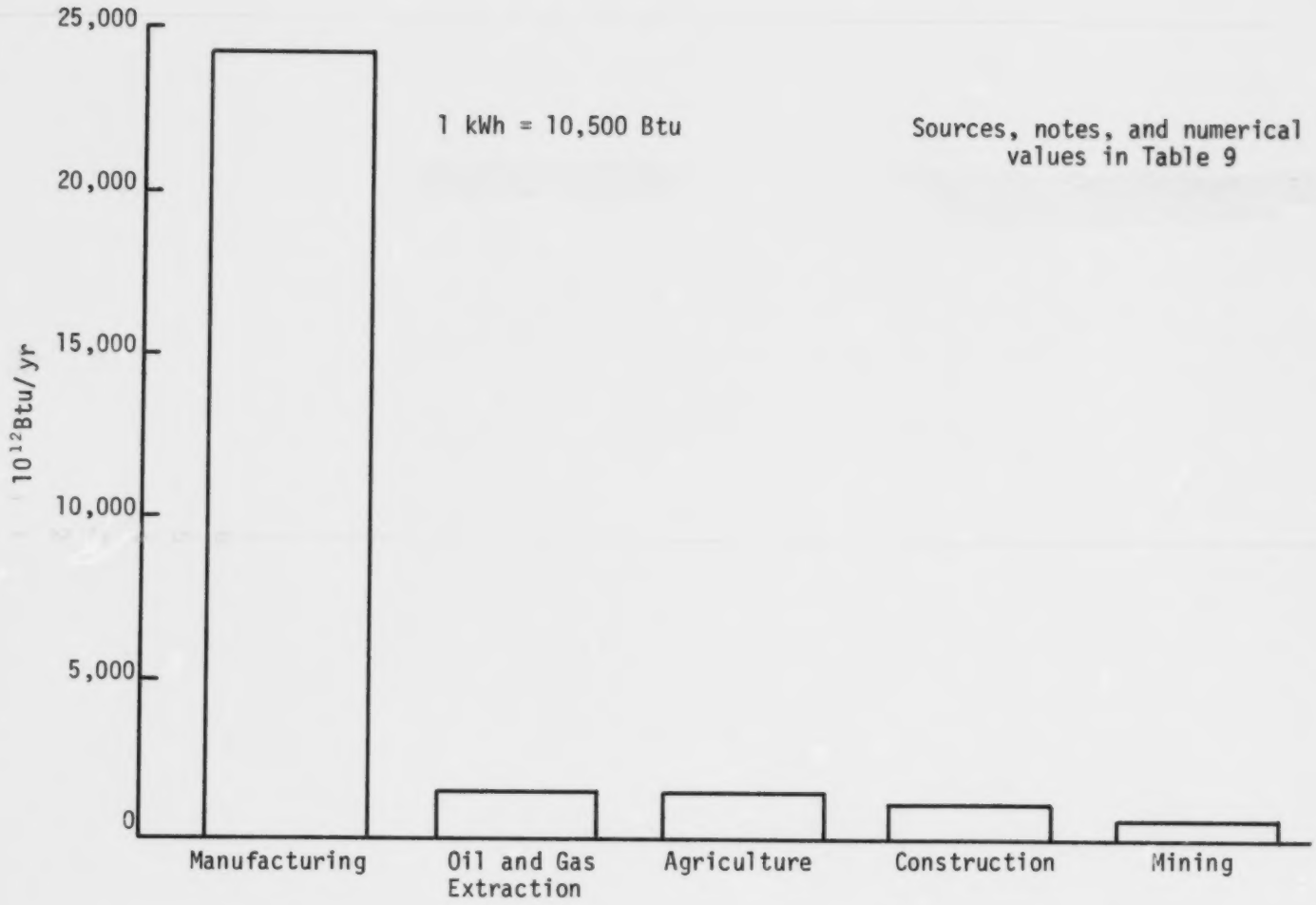

Figure 2. U.S. industrial energy consumption.

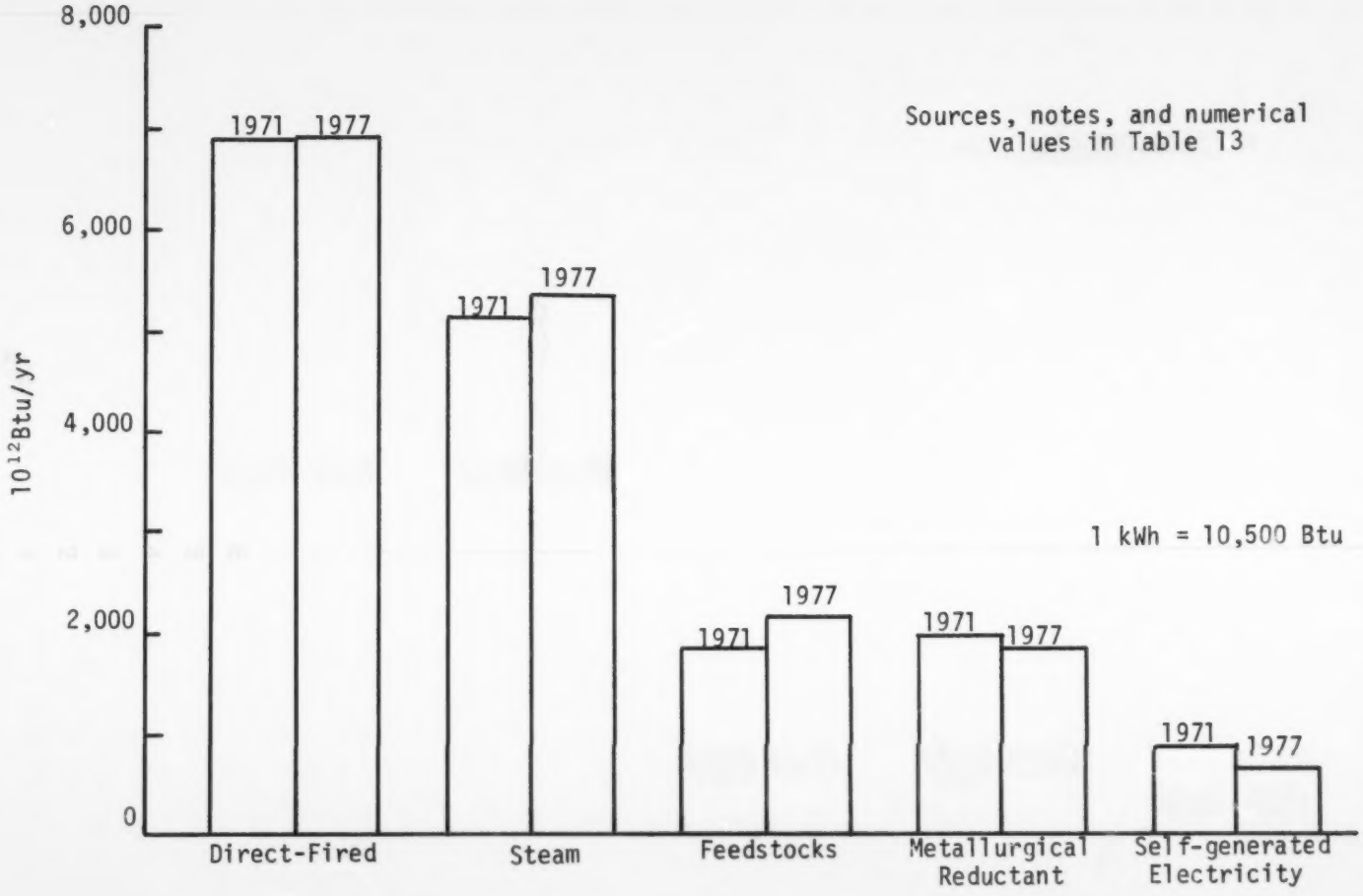

Figure 3. End-Use of Fuel in Manufacturing Industries

TABLE 1. INDUSTRIAL MANUFACTURING ENERGY CONSUMPTION, 10^{12} BTU/YR

Industry Group	SIC	1971[1]	1977[1]
Food and Kindred Products	20	1,173	1,294
Paper and Allied Products	26	2,320[2]	2,395[2]
Chemicals and Allied Products	28	5,172[3]	6,231[3]
Petroleum and Coal Products	29	3,234[4]	2,982[4]
Stone, Clay, and Glass Products	32	1,410	1,494
Primary Metals Industries	33	5,276[5]	5,466[5]
Other Manufacturing		3,666	4,259
Total		22,249	24,122

[1]Purchased fuel energy is from Bureau of the Census (2,3) data, with purchased electricity converted at 10,500 Btu/kWh. Numbers may not add to exact totals due to independent rounding.

[2]Estimate includes 790 x 10^{12} Btu by-product fuel consumption as reported by the American Paper Institute (4).

[3]Estimate includes 1,892 x 10^{12} Btu (1971) and 2,177 x 10^{12} Btu (1977) feedstock energy consumption as estimated from Shell data (5).

[4]Estimate includes 1,498 x 10^{12} Btu captive fuel consumption as reported by the Conference Board (6).

[5]Value includes 2,005 x 10^{12} Btu (1971) and 1,840 x 10^{12} Btu (1977) captive coal consumption as estimated from American Iron and Steel Institute (7) and Battelle (8) information.

TABLE 2. FUEL USE AND PURCHASED ELECTRICITY FOR THE SIX MAJOR MANUFACTURING INDUSTRY GROUPS IN 1977, 10^{12} BTU/YR

Industry group	SIC	Purchased electricity	Self-generated electricity	Steam[2]	Direct-fired[5]	Feed-stocks[3]	Metallurgical reductant[4]	Total[1]
Food	22	448.4	24.6	775.4	45.9	---	---	1,294.3
Paper	26	454.7	287.4	1,602.2	51.1	---	---	2,395.4
Chemicals	28	1,602.3	138.7	729.9	1,583.4	2,177.0	---	6,231.3
Petroleum	29	324.6	46.5	667.6	1,943.6	---	---	2,982.3
Stone, clay and glass	32	336.9	4.6	100.7	1,051.7	---	---	1,493.9
Primary metals	33	1,632.6	139.6	355.0	1,493.0	---	1,845.6	5,465.8
Other manufacturing		2,299.8	22.7	1,142.0	794.2	---	---	4,258.7
Total		7,099.3	664.1	5,372.8	6,962.9	2,177.0	1,845.6	24,121.7

[1]Total energy values are equal to those in Table 10, with purchased and self-generated electricity values obtained from the Bureau of the Census (2,3) data and converted at 10,500 Btu/kWh.

[2]Estimates are based upon data reported by the Institute of Gas Technology (9).

[3]Estimates are based upon Shell (5) data.

[4]Estimates are based upon American Iron and Steel Institute (7) and Bureau of the Census (2,3) data.

[5]Values are obtained by difference.

out. Energy requirements for over 200 processes in the six major industry groups were determined. Collectively, the individual processes identified account for about 70 percent of the manufacturing activity's total direct-fired energy consumption, as shown in Table 3. The balance of the direct-fired fuel is believed to be burned in smaller processes and equipment, such as paint drying, firing of furnaces in small-volume chemical processes, ore roasting, etc.

When the process data were analyzed, it was found that 27 major processes consume over 60 percent of all direct-fired fuel. The distribution by industry is shown in Table 4, and the individual processes are listed in Table 5.

Approximately 80 percent of direct-fired manufacturing processes are fueled by oil and gas, as indicated in Table 6. The greatest reliance on other fuels, particularly coal, occurs in the mineral processing and primary metals industry groups.

The atmospheric emissions from 13 of the 27 direct-fired processes consist solely of products of combustion. These major processes account for about $2,650 \times 10^{12}$ Btu/yr. The balance of $1,600 \times 10^{12}$ Btu/yr is fired in major process equipment which co-mingles combustion gases and other materials from the process (cement kiln, lime kiln, glass furnace, etc.).

For the estimated 7.0×10^{15} Btu/yr of fuel which is direct-fired, as shown in Table 2, an estimated 60 percent, or 4.2×10^{15} Btu/yr, is used in processes which discharge only combustion products. This amount of direct-fired fuel consumed by combustion processes can be contrasted with an estimated 15×10^{15} Btu of fuel burned by utilities and about 10×10^{15} Btu of fuel burned in industrial and commercial boilers in 1975. Further, these processes' strong dependence on oil and gas, which are inherently low in pollution produced per unit of heat output, suggests that this class of direct-fired processes is a relatively unimportant contributor to national pollution levels.

TABLE 3. COMPARISON OF MANUFACTURING DIRECT-FIRED ENERGY CONSUMPTION ESTIMATES, 10^{12} Btu/yr

Industry group	Direct-fired energy consumption based upon total fuel use estimates (1977)[1]	Direct-fired energy consumption based upon process analysis summation[2]
Food	46	155
Paper and allied products	51	40
Chemicals and allied products	1,583	494
Petroleum and coal products	1,944	2,010
Stone, clay and glass products	1,052	829
Primary metals	1,493	1,301
Other manufacturing	794	0
Total	6,963	4,829

[1]Estimates are obtained by difference and are based upon Institute of Gas Technology (9) data. Details and sources are presented in Appendix B.

[2]Details and sources are presented in Appendix B.

TABLE 4. MAJOR DIRECT-FIRED PROCESSES, BY INDUSTRY

Industry	Number of Processes	Energy Consumption, 10^{12} Btu/yr
Petroleum refining	8	1,969
Iron and steel	9	1,075
Mineral processing	4	750
Chemicals	4	414
Nonferrous metals	2	65
Total		4,273

TABLE 5. SUMMARY OF MAJOR ENERGY CONSUMING DIRECT-FIRED PROCESSES

Industry	Process/Operation	10^{12} Btu/yr
Petroleum refining	Atmospheric distillation	529.3
Iron and steel	Slabbing and blooming - reheat furnaces (271.5) - soaking pit (156.3)	427.8
Petroleum refining	Catalytic reforming	407.1
Hydraulic cement	Calcining	324.5
Petroleum refining	Vacuum distillation	296.5
Iron and steel	Blast furnace	267.3
Petroleum refining	Coking (delayed)	266.2
Petroleum refining	Fluid bed catalytic cracker	229.2
Glass	Melting	227.2
Organic chemicals	Ethylene/propylene (thermal cracking)	194.5
Lime	Calcining	145.9
Iron and steel	Coking	144.8
Agricultural chemicals	Ammonia steam reforming	139.0
Petroleum refining	Gas/oil hydrotreating	119.9
Iron and steel	Heat treatment	111.5
Iron and steel	Steelmaking - open hearth furnace (71.8) - basic oxygen furnace (14.4)	86.2
Petroleum refining	Naphtha hydrotreating	77. 8
Brick	Drying/firing	52.8
Organic chemicals	Benzene	44.8
Petroleum refining	Alkylation	42.8
Iron and steel	Cast iron melting - cupola furnace (21.7) - induction furnace (16.1)	37.8
Carbon black	Furnace process	35.7
Primary nonferrous metals	Copper smelting	34.7
Primary nonferrous metals	Alumina calcining	30.0
Total		4,273.3

TABLE 6. COMPOSITION OF DIRECT-FIRED FUEL, BY INDUSTRY GROUP[1]

Industry Group	Total Direct-Fired Energy in 1977, 10^{12} Btu	Oil	Gas	Other Fuels, Including Coal
Food	45.9	0%	97%	3%
Paper	51.1	51%	49%	0%
Chemicals	1,583.4	15%	67%	18%
Petroleum	1,943.6	7%	74%	19%
Stone, Clay, & Glass	1,051.7	14%	46%	40%
Primary Metals	1,493.0	20%	55%	25%
Other Manufacturing	794.2	12%	70%	18%
Total Manufacturing	6,962.9	14%	64%	22%

[1]Estimates based upon information reported by Institute of Gas Technology (IGT) and census data (3,9)

The more important environmental impacts from direct firing of fuel are these associated with processes which discharge combustion gas that is contaminated with other material from the process. Processes of this type emitted about half of the 14.9 million tons of total suspended particulate discharged to the atmosphere in the U.S. in 1976 (16). Many of these processes convert raw materials (such as metal ores) into refined products. Particulates and volatile pollutants, such as fluorides and trace metals, are often emitted during this processing. Most major processes, e.g., cement kilns, blast furnaces, and glass furnaces, have been assessed as general particulate sources. However, they have not been fully evaluated as potential sources of highly hazardous materials. In particular, data relating such emissions to feed composition are limited.

Prospects for fuel switching for this type of process will be limited to introduction of coal where feasible, e.g., in cement kilns and copper smelters. Any change will increase the overall pollution burden to some degree. However, in the absence of better baseline data, the impact of fuel switching would be difficult to assess.

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SECTION 1

INTRODUCTION

The purpose of this project is to add to a comprehensive inventory of current energy use and its environmental impact being prepared by EPA, organized by process or equipment type. This project considers direct-fired processes and equipment.

1.1 OBJECTIVE

The objective of this study was to assess the environmental implications associated with direct-fired energy consumption by the industrial sector. To fulfill this objective, three major tasks were identified:

- determine the amount of direct-fired energy consumed by individual industrial processes and associated equipment,
- evaluate the environmental impact associated with these processes and equipment, and
- determine whether future alterations in present energy consumption patterns for direct firing would have significant environmental impact.

1.2 BACKGROUND

The industrial sector is, from the standpoint of environmental impacts, the most heterogeneous and complex energy consumptive activity and is responsible for 40 percent of this country's total energy consumption (1). In addition, a significant portion of this energy is consumed in direct-fired

processes, which have been the subject of less investigation than other industrial sources, e.g., boilers. Therefore, this analysis investigates the amount of energy fired as direct industrial process heat and the associated environmental implications. In particular, energy consumption patterns and combustion-related emission discharges by several energy-intensive 2-digit SIC industry groups were studied. These groups include food products, paper products, chemical products, petroleum products, stone/clay/glass products, and primary metals. These industry groups consume approximately 80 percent of the industrial manufacturing activity's input energy and include most of the direct-fired processes.

1.3 APPROACH

To carry out the investigation, it was necessary to assemble energy consumption data from numerous studies conducted for nonenvironmental purposes. Then, the amount of energy consumed for various end uses (direct firing, process steam, feedstocks, etc.) within the six industry groups was determined. Finally, the information for direct-fired processes was analyzed, both from an energy consumption basis and from an environmental standpoint. The importance of direct-fired processes as potential sources of pollution is due not only to amount and type of fuel consumed, but also to the type of material processed and the equipment utilized. Therefore, it was not considered appropriate to concentrate on study of the largest sources and omit from consideration those processes identified as small energy consumers. This approach has frequently been used for studies of energy conservation, fuel switching, etc. However, employing this method could have resulted in failure to consider processes which are, or could become because of energy considerations, serious pollution problems.

An alternative approach was selected. Initially, this approach involved analyzing the basic raw materials of the United States, listed in Table 7, and identifying the industries in which they are consumed. Next, recent industrial energy consumption studies and other sources were used to identify

TABLE 7. BASIC RAW MATERIALS FOR UNITED STATES MANUFACTURING INDUSTRIES

Harvested Raw Materials	Extracted Raw Materials
Air	Arsenic
Coffee beans	Asbestos
Cotton	Barite
Grain	Bauxite
Meat animals	Brines and evaporites (borax, chlorine and caustic soda, lithium, magnesium, potash, and sodium)
Milk	Chromite
Seafood	Clays
Sugar crops	Copper ore
Timber	Feldspar
Vegetables, fruits, and nuts	Gold
	Gypsum
	Iron ore
	Lead ore
	Limestone
	Manganese ore
	Molybdenum ore
	Nickel ore
	Oil and gas
	Phosphate rock
	Pumice
	Sand and gravel
	Silicon ore
	Silver ore
	Talc and soapstone
	Tin ore
	Titanium ore
	Tungsten ore
	Uranium
	Vanadium ore
	Zinc ore
	Zirconium ore
	Other minerals (diatomite, graphite, mica, perlite, and vermiculite)
	Other ores (antimony, beryllium, cadmium, mercury, and rare earths)

the direct-fired processes within these industries. Data on energy consumption for specific uses, i.e., direct firing, process steam, feedstocks, metallurgical reductant, and electricity, were then tabulated for the various industry groups and compared with totals shown for energy consumption in other literature sources. Then, the equipment utilized by the direct-fired processes and their associated energy consumptions were identified.

A second energy consumption total was obtained independently from the above estimates. These second figures were obtained by estimating the total amount of each type of fuel, i.e., coal, gas, oil, and other, consumed by each 2-digit SIC industry group and proportioning the fuel among the various end uses, i.e., direct firing, process steam, etc. These overall values, which are industry group- rather than process-specific, were then compared with the values obtained from the summation of the process-specific analysis to determine the amount of energy in each end use category which had been accounted for on a process-specific basis.

When it was determined that most of the significant direct-fired processes had been accounted for, the environmental impacts of these processes were assessed. This involved analysis of both major and minor, yet potentially hazardous, direct-fired processes.

Other energy consumption data were compiled to provide comparisons which were needed to put data from the direct-fired process energy and environmental analysis into perspective. These included: 1) a comparison of energy consumption by all sectors, i.e., residential/commercial, transportation, and industrial; 2) a comparison of energy consumption by manufacturing with consumption by other industrial activities, i.e., mining, agriculture, construction, etc.; and 3) comparisons of energy consumption by different manufacturing industry groups in 1971 and 1977 to determine how consumption for these years compared with data for the years for which process data were available. Also, data were developed to show the types of fuel consumed by major manufacturing industry groups and what these were used for.

Because it was necessary to use information from different sources for various elements of the study, it was impossible to obtain estimates for all components of energy consumption for a single year. As a result, some comparisons of magnitudes of process energy consumption involve estimates of energy consumption in different years from 1971 to 1977. It does not appear from the data, however, that these year-to-year variations in magnitudes of energy consumption are important as far as interpretation of the data is concerned.

The results of the industrial energy consumption analysis are presented in Section 2 and the relevance of data presented to this investigation is discussed. The environmental aspects of direct-fired processes are discussed in Section 3. Conclusions and data needs are presented in Section 4. Detailed total and direct-fired energy consumption data are presented in Appendix A. Methods used in the development of energy consumption data are described in Appendix B.

SECTION 2

ENERGY CONSUMPTION PROFILE

Energy consumption by all sectors in the United States in 1974 totalled 72.6 quads (1 quad = 10^{15} Btu), as shown in Table 8. The industrial sector consumed approximately 40 percent of this energy, 28.5 quads, and was the largest single user.

2.1 INDUSTRIAL ENERGY CONSUMPTION

Manufacturing is the most energy-intensive activity within the industrial sector, as indicated in Table 9. Consuming 24 quads/year of energy, manufacturing accounts for over 80 percent of the industrial sector's energy consumption. For this comparison it was necessary, as indicated in footnotes for Table 9, to use data from different years. It is believed, however, that the data is a reasonable representation of relative values for different industrial activities.

The manufacturing activity is comprised of 20 2-digit Standard Industrial Classification (SIC) industry groups. Six of these groups (food, paper, chemicals, petroleum and coal, mineral processing and primary metals) account for over 80 percent of the manufacturing activity's annual energy consumption, as shown for the years 1971 and 1977 in Table 10.

The only significant increase in energy consumption from 1971 to 1977 occurred in the chemicals industry group. The majority of this increase is attributed to growth in the organic chemicals industry. A sharp increase in demand for the organic chemical industry's products caused a 15 percent increase in production between 1970 and 1976 (13,14). As a result,

TABLE 8. TOTAL ENERGY CONSUMPTION IN U.S. - 1974

Sector	10^{12} Btu/Yr					
	Coal	Coke	Natural Gas	Oil	Purchased Electricity[1]	Total
Residential/ Commercial	314	-	7,518	6,061	11,457	25,350
Industrial	4,347	59	10,018	5,907	8,201	28,532
Transportation	2	-	685	17,720	58	18,465
Other	-	-	-	246	-	246
TOTAL	4,663	59	18,221	29,934	19,716	72,593

Source: U.S. Department of the Interior (1)

[1]Purchased electricity converted at 10,500 Btu/kWh

TABLE 9. INDUSTRIAL ENERGY CONSUMPTION, 10^{12} BTU/YR

Industry activity	Petroleum[1] fuel	Coal/[2] coke	Natural gas	Purchased[3] electricity	Other[4] fuels	Total
Manufacturing[5]	2,120	3,640	5,710	7,100	5,550	24,120
Oil and gas extraction[6]	130	-	1,200	150	-	1,480
Agriculture[7]	970	-	140	330	-	1,440
Construction[8]	1,150	-	20	20	-	1,190
Mining[6]	120	40	230	290	-	680
Total	4,490	3,680	7,300	7,890	5,550	28,910

[1]Estimate includes fuel oil consumption by manufacturing and fuel oil, gasoline, diesel, and LPG consumption by the other industrial activities.
[2]Estimate includes captive coal consumption by the primary metals industry.
[3]Purchased electricity is converted at 10,500 Btu/kWh.
[4]Other fuel's energy consumption includes by-product fuel consumption by the paper industry, feedstock energy consumption by the chemical industry and captive fuel consumption by the petroleum refining industry. This value also includes miscellaneous fuels.
[5]Estimates are based upon 1977 energy consumption data as presented in Table 10.
[6]Estimates are based upon Census (10) data for 1972.
[7]Estimates are based upon U.S. Department of Agriculture, Economic Research Service (11) data for 1978.
[8]Estimates are based upon National Research Council (12) data for 1972.

TABLE 10. INDUSTRIAL MANUFACTURING ENERGY CONSUMPTION, 10^{12} BTU/YR

Industry Group	SIC	1971[1]	1977[1]
Food and Kindred Products	20	1,173	1,294
Paper and Allied Products	26	2,320[2]	2,395[2]
Chemicals and Allied Products	28	5,172[3]	6,231[3]
Petroleum and Coal Products	29	3,234[4]	2,982[4]
Stone, Clay, and Glass Products	32	1,410	1,494
Primary Metals Industries	33	5,276[5]	5,466[5]
Other Manufacturing		3,666	4,259
Total		22,249	24,122

[1]Purchased fuel energy is from Bureau of the Census (2,3) data, with purchased electricity converted at 10,500 Btu/kWh. Numbers may not add to exact totals due to independent rounding.

[2]Estimate includes 790 x 10^{12} Btu by-product fuel consumption as reported by the American Paper Institute (4).

[3]Estimate includes 1,892 x 10^{12} Btu (1971) and 2,177 x 10^{12} Btu (1977) feedstock energy consumption as estimated from Shell data (5).

[4]Estimate includes 1,498 x 10^{12} Btu captive fuel consumption as reported by the Conference Board (6).

[5]Value includes 2,005 x 10^{12} Btu (1971) and 1,840 x 10^{12} Btu (1977) captive coal consumption as estimated from American Iron and Steel Institute (7) and Battelle (8) information.

corresponding increases in the industry's process and feedstock energy requirements were required.

The information presented in Table 10 was derived primarily from Bureau of Census (2,3) data on use of purchased fuels and electricity by manufacturing in the years 1971 and 1977. Information concerning captive fuel consumption in the petroleum, paper, and primary metals industry groups and feedstock requirements in the chemicals industry group was obtained from other sources (4,5,6,7,8).

In Table 11, energy consumption totals from Table 10 are broken down into type and amount of fuel consumed and amount of electricity purchased by major industry groups.

Estimates of captive, by-product, and feedstock energy consumption are included in the applicable categories. For the paper industry group by-product energy consumption totalled approximately 790 x 10^{12} Btu/yr in 1971 as reported by the American Paper Institute (4). This estimate is classified with "other" fuels. The chemicals industry group consumed approximately 1,892 x 10^{12} Btu in 1971 and 2,177 x 10^{12} Btu in 1977 for feedstocks (estimated from References 5, 13, and 14). These values are included in Table 11 as "other" fuels. According to Conference Board data (6), the petroleum refining industry consumed approximately 1,498 x 10^{12} Btu/yr of captive energy in 1971. This value is classified with "other" fuels. Estimates based upon American Iron and Steel Institute data (7) and Battelle information (8) indicate that the metals industry group (particularly iron and steel) consumed 2,005 x 10^{12} Btu (1971) and 1,840 x 10^{12} Btu (1977) of coal as captive fuel. These estimates are included with the "coal" figures.

While data for different years are incomplete, several noteworthy trends are apparent in Table 11. First, most of the major industry groups rely heavily upon natural gas and electricity for their energy needs. The exception to this energy use pattern is the primary metals group, in which a large amount of coal is consumed for coke production in the iron and steel industry.

TABLE 11. INPUT ENERGY OF THE SIX MAJOR MANUFACTURING INDUSTRY GROUPS, 10^{12} BTU/YR

Industry group	SIC	Year	Distillate Oil	Residual Oil	Coal	Coke	Natural gas	Purchased electricity	Other	Total[1]
Food	20	1971	63.5	62.1	116.8	4.0	495.3	371.7	59.4	1,172.8
		1977	79.1	116.8	85.0	1.4	444.7	448.4	118.9	1,294.3
Paper	26	1971	105.4	292.3	247.3	---	493.8	367.5	813.2[2]	2,319.6
		1977	39.1	478.6	213.6	---	360.5	454.7	848.9[2]	2,395.4
Chemicals	28	1971	86.3	119.9	480.1	4.0	1,477.5	1,046.1	1,957.8[3]	5,171.7[3]
		1977	125.3	278.3	341.8	1.3	1,502.6	1,602.4	2,379.6[3]	6,231.3[3]
Petroleum and coal	29	1971	18.9	67.3	9.4	---	1,367.8	248.8	1,521.3[4]	3,233.5
		1977	24.4	47.4	4.8	---	1,063.8	324.6	1,517.3[4]	2,982.3
Stone, clay, and glass	32	1971	64.8	52.9	254.4	8.0	728.7	260.9	40.6	1,410.3
		1977	86.1	76.7	340.9	6.7	541.6	336.9	105.0	1,493.9
Primary metals	33	1971	93.0	131.8	2,253.3[5]	318.0	1,140.7	1,285.3	53.6	5,275.7
		1977	67.7	262.2	2,087.9[5]	359.9	920.3	1,632.6	135.2	5,465.8
Other manufacturing		1971	179.5	158.5	252.7	23.3	977.0	1,855.9	218.7	3,665.6
		1977	178.5	261.5	180.7	12.9	877.5	2,299.8	447.8	4,258.7
Total		1971	611.4	884.8	3,614.0	357.3	6,680.8	5,436.2	4,664.7	22,249.2
		1977	600.2	1,521.5	3,254.7	382.2	5,711.0	7,099.4	5,552.7	24,121.7

[1]Purchased fuel energy is from Bureau of the Census (2,3) data, with purchased electricity converted at 10,500 Btu/kWh.

[2]Estimate includes 790 x 10^{12} Btu by-product fuel consumption as reported by the American Paper Institute (4).

[3]Estimate includes 1,891.8 x 10^{12} Btu (1971) and 2,177.0 x 10^{12} Btu (1977) feedstock energy consumption as estimated from Shell data (5).

[4]Estimate includes 1,498 x 10^{12} Btu captive fuel consumption as reported by the Conference Board (6).

[5]Value includes 2,005 x 10^{12} Btu (1971) and 1,840 x 10^{12} Btu (1977) captive coal consumption as estimated from American Iron and Steel Institute (7) and Battelle (8) data.

Second, manufacturing's consumption of natural gas declined from 1971 to 1977, with purchased electricity and residual oil use increasing significantly. Partly responsible for this trend were the increased price and curtailment of natural gas over this time period -- factors which transferred more of the energy burden to oil and electricity. Also, use of electric furnaces increased, especially in the primary metals industry group (7).

Finally, the data shown in Table 11 indicate that coal use in the manufacturing activity declined from 1971 to 1977. This reduction occurred despite increased prices of premium fuel oils and natural gas.

2.2 INDUSTRIAL MANUFACTURING DIRECT-FIRED ENERGY CONSUMPTION

The fuels consumed in the manufacturing portion of the industrial sector are used in five basic ways: 1) to generate on-site electricity; 2) to produce process and space heating steam in industrial boilers; 3) to provide direct-fired process heat; 4) to provide chemical feedstocks; and 5) to provide a reducing agent in metallurgical processing. Direct-fired heat accounts for approximately 40 percent of the fuel use, as shown in Table 12. The production of steam, excluding that amount used to generate on-site electricity, requires about 30 percent of the total input fuel energy. Steam produced by heat recovery, i.e., waste heat boilers, is not included in this figure. Only "fired" boilers are included in the process steam category.

An attempt was made to determine the primary function of the fuel fired, i.e., whether it was required to provide process heat, or whether it was required to produce a reducing atmosphere necessary to obtain a desired chemical reaction. Information from different sources (7,8) was used to assign process fuel consumption to the direct-fired (heat) category or to the reducing atmosphere category. Essentially all of the fuel used to provide a reducing atmosphere, or the metallurgical reductant, is consumed in the primary metals industry group.

TABLE 12. END USE OF FUEL IN THE INDUSTRIAL MANUFACTURING SECTOR, %

	1971	1977
Self-generated electricity	5.2	3.9
Process and space heating steam	30.6	31.6
Direct-fired heat	41.2	40.9
Chemical feedstock	11.3	12.8
Metallurgical reductant	11.7	10.8
	100.0	100.0

The percentage breakdowns in Table 12 are derived from data presented in Table 13, which apportions major industry groups' energy consumption by end use. Although purchased electricity energy was not included in the calculation of the percentage breakdowns, it is included in Table 13 to balance the totals (from Table 11) and to provide perspective. Methods used in developing this data are detailed in Appendix B.

The total manufacturing direct-fired energy consumption figure, 7,000 x 10^{12} Btu, compares reasonably well with other reported values, such as the 6,600 x 10^{12} Btu direct-fired energy consumption estimated for the industrial sector in 1968 (15). This general agreement tends to support the validity of the assumptions made and the methods used in the development of the data presented in Table 13. Furthermore, the amounts of direct-fired energy accounted for on a process-specific basis (shown in Table 14 and detailed later) agree, for the most part, with the industry group direct-fired totals shown in Table 13.

The results in Table 13 show that four of the six major industry groups in the manufacturing activity use essentially all of the direct-fired process heat. The food and paper industry groups show a strong dependence on process steam energy but minimal use of direct-fired energy. The other four groups rely upon direct firing for a large portion of their process energy requirements,

TABLE 13. FUEL USE AND PURCHASED ELECTRICITY FOR THE SIX MAJOR MANUFACTURING INDUSTRY GROUPS, 10^{12} BTU/YR

Industry group	SIC	Year	Purchased electricity	Self-generated electricity	Steam[2]	Direct[2] fired	Feed-[3] stocks	Metallurgical[4] reductant	Total[1]
Food	20	1971	371.7	27.3	720.3	53.5	---	---	1,172.8
		1977	448.4	24.6	775.4	45.9	---	---	1,294.3
Paper	26	1971	367.5	266.5	1,631.1	54.5	---	---	2,319.6
		1977	454.7	287.4	1,602.2	51.1	---	---	2,395.4
Chemicals	28	1971	1,046.1	205.4	680.4	1,348.0	1,891.8	---	5,171.7
		1977	1,602.3	138.7	729.9	1,583.4	2,177.0	---	6,231.3
Petroleum	29	1971	248.8	56.7	758.6	2,169.4	---	---	3,233.5
		1977	324.6	46.5	667.6	1,943.6	---	---	2,982.3
Stone, clay, and glass	32	1971	260.9	9.4	110.9	1,029.1	---	---	1,410.3
		1977	336.9	4.6	100.7	1,051.7	---	---	1,493.9
Primary metals	33	1971	1,285.3	258.4	200.5	1,556.5	---	1,975.0	5,275.7
		1977	1,632.6	139.6	355.0	1,493.0	---	1,845.6	5,465.8
Other		1971	1,855.9	45.2	1,047.4	717.1	---	---	3,665.6
		1977	2,299.8	22.7	1,142.0	794.2	---	---	4,258.7
Total		1971	5,436.2	868.9	5,149.2	6,928.1	1,891.8	1,975.0	22,249.2
		1977	7,099.3	664.1	5,372.8	6,962.9	2,177.0	1,845.6	24,121.7

[1]Total energy values are equal to those in Table 10, with purchased and self-generated electricity values obtained from the Bureau of the Census (2,3) data and converted at 10,500 Btu/kWh.

[2]Estimates are based upon data reported by the Institute of Gas Technology (9).

[3]Estimates are based upon Shell (5) data.

[4]Estimates are based upon American Iron and Steel Institute (7) and Bureau of the Census (2,3) data.

[5]Values are obtained by difference.

especially petroleum refining and stone/clay/glass products. In the chemical and primary metals industry groups, reliance on direct-fired energy and electricity is about equal.

The energy consumption data presented in the previous tables have been developed on an industry group or overall industry basis. The following tables present the results of an analysis of major industrial processes within these industry groups. The energy requirements of these processes were then tabulated to obtain an energy use profile independent of the other data.

A summation of the amount of energy in each end use category for which process-specific information was available is presented in Table 14. This table shows that over 60 percent of the energy consumed in all manufacturing operations was accounted for by specific processes within the six major industry groups presented in Table 14. The percentages of energy accounted for in specific categories, as compared to 1977 data in Table 13, are as follow:

Electricity	41.5%
Steam	70.1%
Direct-fired	69.4%
Feedstock	89.4%
Metallurgical reductant	74.3%
Total	62.7%

As shown by these percentages, approximately 40 percent of the energy consumed as electricity in all manufacturing industry groups was accounted for by investigating the six major groups on a process-specific basis. The remaining electrical energy is evidently consumed in a variety of minor processes and for non-process purposes (lighting, plant HVAC systems, product handling, etc.).

Approximately 70 percent of the energy consumed to produce steam for manufacturing operations was allocated to specific processes within the six major

TABLE L4. SUMMATION OF PROCESS ENERGY ANALYSIS FOR SIX MAJOR INDUSTRY GROUPS, 10^{12}BTU/YR[4]

Industry Group	SIC	Electrical[2]	Process Steam	Direct-Fired	Feed-stocks	Metallurgical Reductant	Total[1]
Food	20	471.0	671.4	155.0	---	---	1,297.4
Paper	26	634.0	1,645.8	39.7	---	---	2,319.6
Chemicals	28	530.0	720.7	494.4	1,945.8	17.4[3]	3,708.3
Petroleum	29	175.4	486.5	2,010.1	---	---	2,672.0
Stone, Clay, and Glass	32	199.8	---	829.0	---	---	1,028.9
Primary Metals	33	1,210.0	240.5	1,300.6	---	1,353.5	4,104.5
Total[1]		3,220.2	3,764.9	4,828.8	1,945.8	1,370.9	15,130.7

[1]Numbers may not add to exact totals due to independent rounding.
[2]Estimate includes purchased and self-generated electricity converted at 10,500 Btu/kWh.
[3]Estimate includes coke used in the production of elemental phosphorus and sodium metal.
[4]Methodology and sources are presented in Appendix B.

industry groups. The balance is evidently used in minor industrial processes and for non-process purposes, such as space heating.

Almost 90 percent of the feedstock energy consumed in the chemicals industry group was used in the manufacture of approximately 20 high production volume chemicals, as listed in Appendix A, Table A-1. The unaccounted-for balance is used as feed to several hundred relatively minor chemical processes.

Three-fourths of the coal, or coke, consumed as metallurgical reductant by the industrial sector was accounted for by specific processes within the chemicals and primary metals industry groups. The balance is evidently consumed in relatively minor processes, such as secondary lead smelting, within the primary metals industry group.

Approximately 70 percent of the annual direct-fired energy consumption, $4{,}800 \times 10^{12}$ Btu of $7{,}000 \times 10^{12}$ Btu, was accounted for by specific manufacturing processes within the six most energy-intensive industry groups. The character of these direct-fired processes in these industry groups varies greatly. The industries range from those dominated by a few major processes to those made up predominantly of many small consuming operations.

The food industries use direct firing for less than five percent of their total energy needs. Most of the direct-fired energy is used for feed drying, beet sugar drying, baking, and miscellaneous drying. The relatively small amount of direct-fired fuel and the lack of detailed information on how it is used in the food industries prevented a reasonable comparison of process-specific and total direct-fired fuel use, as shown in Table 3. However, the food industry group is a comparatively minor direct-fired energy user, consuming about 100×10^{12} Btu/yr of the $7{,}000 \times 10^{12}$ Btu/yr consumed in all direct-fired industrial processes.

Paper processing industries, like the food industries, are relatively minor consumers of direct-fired energy, using about 50×10^{12} Btu/yr.

Approximately 40 x 10^{12} Btu is consumed annually in two processes in the paper industry group, coated paper drying and white liquor production (lime kilns).

The chemical industries utilize large quantities of direct-fired fuel (almost 1,600 x 10^{12} Btu in 1977). Four major specific processes account for about 410 x 10^{12} Btu/yr of this total with 24 minor processes consuming an additional 80 x 10^{12} Btu/yr. Because of the broad diversification of the various chemical industries, only the high production volume chemicals were investigated on an individual basis. Therefore, direct-fired processes used in the production of several hundred minor chemicals were not assessed, and these processes contribute to the unaccounted-for balance of direct-fired energy consumed in this group.

The petroleum industry group is the largest consumer of direct-fired energy, using approximately 2,000 x 10^{12} Btu/yr. Essentially all of this energy was allocated to 10 specific manufacturing processes in the petroleum refining industry, as detailed in Table A-2 of Appendix A.

The stone/clay/glass and primary metals industry groups are major consumers of direct-fired energy, using 1,000 x 10^{12} Btu/yr and 1,500 x 10^{12} Btu/yr, respectively. Approximately 80 percent of this energy was accounted for by individual direct-fired processes within these groups. The balance is evidently consumed in many relatively minor processes, such as drying, calcining, melting, etc.

Although data were obtained to determine all major process- or product-related energy consumption, only those processes utilizing direct-fired energy were studied in detail. The purpose of including all types of energy consumption in this analysis was to determine what percentage of total energy consumption had been accounted for and to determine the significance of direct-fired energy as compared with other forms, primarily electricity and process steam.

A summary of the major energy consuming processes and/or industries in the six major industry groups is presented in Table 15. The raw material used and the amounts of energy consumed by each major process/products are shown. These top 21 process/products account for approximately 84 percent of the total energy accounted for by the process analysis. All of the process/products analyzed in this study are included in Table A-1 in the Appendix. It is significant to note from Table 15 that the amount of energy consumed in direct-fired processes is quite substantial as compared to the amounts of energy consumed for steam production and electricity use. This is especially true in the petroleum refining and iron and steel industries.

From the information presented in Tables 15 and A-1, identification of processes utilizing direct-fired energy was made. These processes are presented in Table A-2 in the Appendix, with the major processes summarized in Table 16. This table shows that most of the major direct-fired energy consumers are those processing oil and gas and iron ore raw materials. These processes are in the petroleum refining, organic chemicals, and iron and steel industries. In addition, the cement, copper, aluminum, lime, and glass industries include at least one significant direct-fired process. The direct-fired processes are characterized by several large consumers, with the major 27 processes accounting for over 60 percent of the direct-fired energy total shown in Table 13.

Industrial direct firing takes place in various types of equipment. These types include specifically engineered process equipment and "off-the-shelf" equipment. The types of equipment used in direct-fired processes and estimates of energy consumption associated with these equipment types are presented in Table A-3 in the Appendix.

TABLE 15. SUMMARY OF MAJOR PROCESS- OR PRODUCT-RELATED ENERGY CONSUMPTIONS, 10^{12} BTU/YR

Raw Material	Process/Product	SIC	Date	Electricity[3]	Direct-Fired	Process Steam[2]	Feedstock	Metallurgical Reductant	Total[1]
Iron ore	Iron and steel	331/332	1975	370.60	1,145.07	127.78	-	1,264.25	2,907.71
Timber	Paper products	26	1971	634.03	39.75	1,645.82	-	-	2,319.60
Oil and gas	Ethylene propylene	2869	1971	11.91	194.46	174.61	1,079.43	-	1,460.41
Bauxite	Aluminum	3334	1975	663.70	41.93	106.25	-	51.47	863.35
Oil and gas	Crude distillation	2911	1973	32.40	529.30	87.90	-	-	649.60
Oil and gas	Ammonia	2873	1975	4.79	139.00	125.63	368.29	-	637.70
Oil and gas	Fluid bed catalytic cracker	2911	1973	41.90	229.20	208.70	-	-	479.80
Oil and gas	Catalytic reforming	2911	1973	21.80	407.10	32.70	-	-	461.60
Limestone	Cement	3241	1971	105.38	324.50	-	-	-	429.88
Chlorine and caustic soda	Chlorine and caustic soda	2812	1973	198.94	-	214.14	-	-	413.08
Oil and gas	Vacuum distillation	2911	1973	17.70	296.50	48.80	-	-	363.00
Sand and gravel	Glass	3211/3221/3229	1973	59.30	258.52	-	-	-	317.82
Oil and gas	Delayed coking	2911	1973	11.70	266.20	33.00	-	-	310.90
Oil and gas	Gas oil hydrotreating	2911	1973	29.60	119.90	14.80	-	-	164.30
Limestone	Lime	3274	1975	11.38	145.85	-	-	-	157.24
Oil and gas	Ethylbenzene/styrene	2865	1971	3.97	19.84	27.78	87.31	-	138.90
Oil and gas	Carbon black	2895	1971	-	39.68	-	99.21	-	138.89
Grain	Prepared feeds, pet food	2047/2048	1971	69.97	23.07	37.16	-	-	130.20
Copper ore	Copper	3331	1975	63.34	58.03	(5.81)	-	-	115.56
Meat animals	Meat packing	2011	1971	36.96	5.26	67.05	-	-	109.27
Oil and gas	Naphtha hydrotreating	2911	1973	12.30	77.80	12.30	-	-	102.40
				2,401.67	4,360.96	2,958.61	1,634.24	1,315.72	12,671.21

[1]Numbers may not add to exact totals due to independent rounding.

[2]Steam credits are shown in parentheses.

[3]Purchased and self-generated electricity are converted at 10,500 Btu/kWh.

[4]Methodology and sources are presented in Appendix B.

TABLE 16. SUMMARY OF MAJOR ENERGY CONSUMING DIRECT-FIRED PROCESSES

Raw Material	SIC	Industry	Process/Operation	10^{12} Btu/yr
Oil and gas	2911	Petroleum refining	Atmospheric distillation	529.3
Iron ore	331/332	Iron and steel	Slabbing and blooming - reheat furnaces (271.5) - soaking pit (156.3)	427.8
Oil and gas	2911	Petroleum refining	Catalytic reforming	407.1
Limestone	3241	Hydraulic cement	Calcining	324.5
Oil and gas	2911	Petroleum refining	Vacuum distillation	296.5
Iron ore	331/332	Iron and steel	Blast furnace	267.3
Oil and gas	2911	Petroleum refining	Coking (delayed)	266.2
Oil and gas	2911	Petroleum refining	Fluid bed catalytic cracker	229.2
Sand and gravel	3211/3221 /3229	Glass	Melting	227.2
Oil and gas	2869	Organic chemicals	Ethylene/propylene (thermal cracking)	194.5
Limestone	3274	Lime	Calcining	145.9
Iron ore	331/332	Iron and steel	Coking	144.8
Oil and gas	2873	Agricultural chemicals	Ammonia steam reforming	139.0
Oil and gas	2911	Petroleum refining	Gas/oil hydrotreating	119.9
Iron ore	331/332	Iron and steel	Heat treatment	111.5
Iron ore	331/332	Iron and steel	Steelmaking - open hearth furnace (71.8) - basic oxygen furnace (14.4)	86.2
Oil and gas	2911	Petroleum refining	Naphtha hydrotreating	77.8
Clays	3251	Brick	Drying/firing	52.8
Oil and gas	2865	Organic chemicals	Benzene	44.8
Oil and gas	2911	Petroleum refining	Alkylation	42.8
Iron ore	331/332	Iron and steel	Cast iron melting - cupola furnace (21.7) - induction furnace (16.1)	37.8
Oil and gas	2895	Carbon black	Furnace process	35.7
Copper ore	3331	Primary nonferrous metals	Copper smelting	34.7
Bauxite	3334	Primary nonferrous metals	Alumina calcining	30.0
				4,273.3

SECTION 3

POLLUTION POTENTIAL PROFILE

The industrial sector emits approximately 30 x 10^6 tons of uncontrolled criteria pollutants per year (16), an emission rate comparable with that of the electric utility sector. Industrial emissions of special significance are particulates and hydrocarbons, which account for approximately 50 percent and 40 percent of the national emission discharges of these pollutants from all sources, respectively. Of lesser importance are sulfur oxide (SO_x), carbon monoxide (CO), and nitrogen oxide (NO_x) emissions. The industrial sector is also responsible for substantial emissions of trace and volatile metals and other potentially hazardous non-criteria pollutants which do not appear to have been fully evaluated.

A large portion of these industrial emissions can be attributed to direct-fired processes. These emissions include products of combustion and pollutants from the process material itself, e.g., volatile metals from blast furnaces, dust from cement kilns, particulates from glass melting furnaces, etc.

In Section 3.1 are analyzed the environmental implications associated with the most energy-intensive direct-fired processes, shown in Table 16. The pollution potential of other potentially hazardous direct-fired processes is discussed in Section 3.2.

3.1 MAJOR PROCESSES

The direct-fired processes classified as major energy consumers (the 27 processes which consume at least 30 x 10^{12} Btu/yr of direct-fired fuel) are

analyzed from an environmental standpoint in this section. These energy-intensive processes are listed in Table 16.

3.1.1 Petroleum Refining/Chemicals

The eight largest direct-fired processes in the petroleum refining industry consume almost 98 percent, or about 1,970 x 10^{12} Btu/yr, of the direct-fired energy accounted for in this industry. The petroleum industry's total direct-fired energy consumption as determined by the process energy analysis, 2,010 x 10^{12} Btu/yr, is essentially all of the industry's direct-fired energy consumption as determined from fuel use estimates (Table 13). In addition, these eight major petroleum refining processes consume about 30 percent of all of the direct-fired fossil fuel in the U.S. industrial sector. These processes are:

- atmospheric distillation,
- catalytic reforming,
- vacuum distillation,
- delayed coking,
- fluid catalytic cracking,
- gas oil hydrotreating,
- naphtha hydrotreating, and
- alkylation.

In addition, four major processes in the chemicals industry group consume about 6 percent of all the direct-fired fossil fuel in the U.S. These are:

- ethylene/propylene production,
- steam-hydrocarbon reforming (ammonia),
- benzene production, and
- furnace black (carbon black).

These four major processes consume over 80 percent, or 414 x 10^{12} Btu/yr of the direct-fired energy accounted for in the chemicals industry group. The remaining 24 processes identified consume the remaining 80 x 10^{12} Btu/yr. The chemical industry group's total direct-fired energy consumption as determined by the process energy analysis, 494 x 10^{12} Btu/yr, is approximately 1,000 x 10^{12} Btu/yr less than the industry group's direct-fired energy consumption total as determined from fuel use estimates (Table 13). The difference is attributed to numerous unaccounted for processes and equipment, such as fired heaters in the highly diversified organic chemicals industry and dryers in the inorganic chemicals industry.

Except for two processes, fluid catalytic cracking and furnace black, the pollutants emitted by these petroleum refining and chemical industry processes consist only of products of combustion. The direct firing takes place in a process heater with the process fluid on the tube side. The firebox conditions do not vary significantly from unit to unit, so fuel type is the only significant variable affecting the emissions. The fuels utilized in these processes consist primarily of "make gas" with lesser dependence on residual and distillate oil. The petroleum refining industry also consumes a significant amount of natural gas and by-product fuels, primarily acid sludges and petroleum coke. The pollutants from the combustion of these fuels are primarily NO_x and CO, with small amounts of hydrocarbons, SO_x, and particulates.

For these processes there is a limited likelihood of changing fuel patterns such as a switch to coal. The nature of the processes and the availability of fuel as raw material and of by-product fuels indicate little potential for coal firing. There is the possibility of using direct combustion of asphalt in process furnaces and boilers. This could result in significant increases in SO_x emissions. This would probably require that flue gas desulfurization control technology be installed to reduce these emissions (17). No particulate controls are currently used for gas-fired and oil-fired heaters but may be required for asphalt-fired furnaces.

The only major process in the petroleum refinery industry that should be discussed separately is fluid catalytic cracking. Major equipment types in this process include the fluid catalytic cracker and CO boiler. Coke is deposited on the catalyst surface as a by-product of the cracking reaction. This coke must be burned off to restore catalyst activity and is therefore a captive fuel source. The coke is burned off in the regenerator with substoichiometric air addition, resulting in an off-gas stream containing:

- high CO concentrations,
- high particulate loadings (catalyst fines),
- high SO_x concentrations,
- low to moderate hydrocarbon concentrations, and
- low to moderate NO_x concentrations.

This stream is typically controlled by use of a CO boiler to finish combustion of the CO and any hydrocarbons present. Particulates are controlled using electrostatic precipitators, while SO_x and NO_x are typically uncontrolled.

The furnace black process for carbon black in the chemical industry group is the only major process in this industry group which should be discussed separately. The combustion products from the furnace process also contain the product carbon particulates. These must be filtered out to obtain the product. Essentially all of these particulates are removed for economic as well as environmental considerations. Therefore, there appears to be no significant impact on a local or national basis from this process.

3.1.2 Iron and Steel

The 11 major processes in the primary metals industry group, ferrous and nonferrous, account for almost 88 percent, or $1,143 \times 10^{12}$ Btu/yr, of the direct-fired energy accounted for in this group. Most of this energy ($1,078 \times 10^{12}$ Btu/yr) is consumed in major iron and steel processes. The balance (65×10^{12} Btu/yr) is consumed in major nonferrous metal operations. Another

74 smaller processes which were identified consume an additional 160 x 10^{12} Btu/yr. The primary metals industry group's total direct-fired energy consumption as determined by the process energy analysis, 1,300 x 10^{12} Btu/yr, is approximately 200 x 10^{12} Btu/yr less than the industry group's direct-fired energy consumption total as determined from fuel use estimates (Table 13). This difference is attributed to numerous small furnaces, heaters, and other miscellaneous fired equipment.

Approximately 15 percent of this country's direct-fired energy consumption occurs in nine major processes in the iron and steel industry, according to the process energy consumption analysis. The energy-intensive direct-fired processes include:

- coking (coke oven)
- blast furnace,
- steel making,
  - open hearth furnace
  - basic oxygen furnace
- slabbing and blooming
  - reheat furnace
  - soaking pit furnace
- heat treatment (heat treating furnace), and
- cast iron melting
  - cupola furnace
  - induction furnace

With the exception of the slabbing/blooming and heat treatment processes, the energy-intensive iron and steel production processes are significant potential sources of emissions other than combustion products. The iron and steel industry emits approximately 7 percent of the national particulate emissions and less than 2 percent of other criteria pollutants (18). The high particulate emission level can have a severe local environment impact.

The coke ovens, fired with recycled coke oven gas, are sources of perhaps the industry's worst pollution problems. Emissions include unburned hydrocarbons (some carcinogenic), SO_x, and trace metals. A significant

amount of the gaseous emissions are controlled by drawing off the exhausted gas stream for product recovery. Since coking emissions are highly process-related and are not strongly affected by the fired fuel (coke oven gas), no significant changes in emission types or levels are anticipated. Dry quenching of coke is a newer technology with the potential to reduce emissions and overall energy requirements, but widespread U.S. acceptance of this process is not expected to occur in the near future (19).

The blast furnace is a source of particulate and volatile metal emissions, but these and other gaseous pollutants are controlled so that the blast furnace gas can be recycled as fuel. The emission rates are a strong function of production level, with less dependence on type of fuel fired (blast furnace gas, coke oven gas, oil, and natural gas). Therefore, substantial changes in blast furnace energy consumption and emission rates are not expected in the near future. A newer technology, the direct-reduction electric-furnace process, eliminates the need for metallurgical coke and would result in a cleaner industry at the expense of greater gross energy requirements. However, prospects for widespread U.S. acceptance of this technology are not good (19).

Steelmaking involves two major direct-fired processes, the open hearth furnace (OHF) and the basic oxygen furnace (BOF). Both processes, and especially the BOF, are controlled sources of substantial particulate and volatile metal emissions. In addition, the BOF process is a source of high CO emission levels. Because the BOF process is characterized by higher production rates and lower manufacturing costs, the industry is increasing its reliance on this process, with gradual phasing out of the OHF process. This trend has the effect of lowering the industry's fuel requirements at the expense of higher pollution loadings. Fuels fired include natural gas (BOF and OHF), oil (OHF), tar and pitch (OHF), and coke oven gas (OHF); fuel switching would not greatly alter the primarily process-related emission levels.

The reheat furnaces, soaking pit furnaces, and heat treating furnaces are the equipment used for the heating of semi-finished steel in the slabbing/blooming and heat treatment processes. The emissions associated with these processes are products of combustion; therefore, firing of fuels other than the conventional fuels (natural gas, fuel oil, and coke oven gas) could have a significant impact on type and amount of emissions.

Cast iron melting is done in cupola furnaces and electric induction furnaces (supplementally fired). Furnaces, particularly cupolas, are controlled sources of trace and volatile metals; the type of fired fuel (natural gas and fuel oil) has relatively little impact on the emission level. The recent trend toward increased electric melting because of environmental and product quality considerations has the effect of lowering emission levels from cast iron melting operations.

3.1.3 Mineral Processing

Four major mineral conversion processes consume about 11 percent of all of the direct-fired fossil fuel in the U.S. These are:

- cement kilns,
- glass melting furnaces,
- lime kilns, and
- brick kilns.

Most of the fuel burned in these processes is gas or oil although coal is becoming more important for cement or lime production. Where coal is used, SO_x which is formed will often react with the alkaline feed materials and be collected along with dust leaving the kiln, if the alkali to sulfur ratio is sufficiently high.

Recent studies have analyzed new techniques for glass melting, which is predominantly accomplished in natural gas-fired glass furnaces. These

new technologies use direct coal firing, coal gasification, hot gas generation, and electricity for process heat (20). These processes would increase gross energy consumption and escalate emission levels (at the power generating plant in the case of electric melting). However, dependence on natural gas would decline in favor of coal.

The most important pollutant from all mineral processing is fine particulate, which amounted to 3.5 million tons of the 14.9 million tons estimated from all sources in 1976 (16). Cement, lime, and glass production account for a significant percentage of all particulate emissions from mineral processing, but the amounts produced are affected only slightly by type of fuel used; hence, future pollution problems are not likely to be impacted by changes in energy use patterns.

3.1.4 Primary Nonferrous Metals

There are two major processes in the primary nonferrous metals industry which together consume about 1 percent of the total direct-fired fossil fuel in the U.S. industrial sector. These processes are:

- copper reverberatory smelting and
- alumina calcination.

In both of these processes, the products of combustion from direct firing are contaminated with process material.

Copper reverberatory smelting is a significant source of SO_x, particulate, and volatile metal fume emissions. These pollutants are combined with the products of combustion, including CO and NO_x. The fuels fired in the reverberatory furnace are primarily oil and natural gas. It is technically feasible to burn coal in these furnaces, and rising fuel prices may initiate a switch to coal. This trend could result in increased particulate, SO_x, and NO_x emissions. Particulate emissions from this process are typically

controlled by an electrostatic precipitator. Sulfur dioxide and nitrogen oxide emissions are not controlled.

There are several new smelting processes which have lower energy requirements and less environmental impact than the reverberatory smelting process. These processes are the Noranda, Outokumpu, and Mitsubishi smelting processes. These processes are 30 to 50 percent more energy-efficient than conventional reverberatory smelting. They also allow higher levels of sulfur recovery--over 90 percent. These processes can utilize gas, oil, or coal as fuel. These new processes will have limited short-term impact in the U.S. because these technologies have not been demonstrated on the impure feeds processed by many of the domestic copper producers (21).

The calcination of hydrated alumina takes place in natural gas-fired kilns. High grade fuel oil can also be fired in most cases. The products of combustion are contaminated with fine particulates of alumina. These particulates of alumina are valuable and extensive controls are used to reduce these emissions to small quantities.

There is limited potential for switching to coal since the alumina product from these kilns must be fairly pure.

3.2 MINOR PROCESSES

Certain processes that consume relatively little direct-fired energy may have considerable environmental impact. These processes are discussed by industry group in this section and are listed in Table A-2 in the Appendix.

3.2.1 Chemicals

The lesser organic chemical processes present, on a smaller scale, environmental problems similar to those of the major organic chemical processes, i.e., products of combustion. The inorganic chemical segment's environmental

impact is determined to be minor, with process-related emissions from direct-fired dryers and roasters being potentially hazardous.

3.2.2 Petroleum Refining

The only other important petroleum refining processes which are not included in the major processes are thermal cracking, which consumes about 23.4×10^{12} Btu/yr of direct-fired energy, and visbreaking, which consumes about 17.9×10^{12} Btu/yr. These processes are similar to the major processes from an environmental standpoint, in that they are characterized primarily by combustion product emissions.

3.2.3 Mineral Processing

Most minor direct-fired processes identified in the stone/clay/glass industry group are for drying or calcining of raw materials or products. These 19 identified processes consume only 10 percent of the direct-fired energy accounted for in the mineral processing industry group. As a result, the amounts of particulate and combustion product emissions from individual processes are determined to have relatively minor local and national environmental impacts.

Approximately 80 percent of the mineral processing industry group's direct-fired energy was accounted for by the process energy analysis, as noted by comparison of Tables 13 and 14. Various unaccounted-for processes, including drying, calcining, and heating apparently contribute to the discrepancy.

Asbestos fiber drying poses potentially serious particulate problems, but dust emissions appear to be effectively controlled with conventional technology.

3.2.4 Primary Metals (Ferrous and Nonferrous)

Sintering of iron ore requires relatively little direct-fired energy in the primary metals industry group. However, sintering machines, in addition to coke ovens, are the principal sources of emissions in the iron and steel industry (22). Sintering emissions include particulates and SO_x. These pollutants are primarily process-related and are not strongly dependent upon the fired fuel (predominantly natural gas). Emission discharges are limited by conventional control technology.

The carbon anode baking process in the aluminum segment of the primary metals industry group is one of the largest consumers of direct-fired energy in the non-major category. It is also one of the most significant sources of emissions in the aluminum industry. The emissions consist of products of combustion from the oil or gas burners and organics, fluorides, SO_x, and fine coke dust from the anode. Several methods of control are used to reduce these emissions, including spray towers and electrostatic precipitators.

3.2.5 Food and Paper

The food and paper industry groups are characterized by relatively little direct firing. The predominantly gas- and oil-fired processes in these groups emit primarily products of combustion, rather than hazardous process materials. Because of the amount of fuel burned in these processes and the nature of the process emissions, environmental impacts from direct-fired processes in the food and paper industry groups were assessed to be minor.

SECTION 4

CONCLUSIONS AND DATA NEEDS

This section presents conclusions and data needs based on the energy consumption profile analysis and the pollution potential profile analysis discussed in Sections 2 and 3.

4.1 CONCLUSIONS

Conclusions resulting from the analysis of direct-fired energy consumption and the associated environmental implications are presented here.

4.1.1 Energy Consumption Profile Analysis

Several important conclusions are evident from the energy consumption profile analysis:

- Direct firing of fossil-based fuels accounts for about 25 percent (7 quads/yr) of all industrial energy use. This amount of direct-fired energy is about 10 percent of the total annual fuel consumption in the U.S.
- Approximately 80 percent of direct-fired fuel is oil or gas.
- Almost 90 percent of the direct-fired energy is consumed in four industrial groups: petroleum, primary metals, chemicals, and stone/clay/glass.
- About 60 percent of all direct-fired energy is consumed in 27 major processes employed for the production of petroleum refinery products, primary metals (iron, steel, copper, aluminum), chemicals (ethylene, propylene, benzene, carbon black, and ammonia), and mineral products (cement, glass, lime, and bricks).

- Conversion of a significant number of these 27 processes to coal, gas made from coal, or electricity generated from coal would have a significant impact on consumption of premium fuels.

- Switching of some of these direct-fired processes, e.g., cement kilns and reverberatory furnaces for copper production, to coal has been shown to be feasible and practical. Other processes are unlikely candidates for switching to coal despite the possible technical feasibility of burning coal. For example, switching refinery operations which burn gas, much of which is a by-product from other operations, to coal seems unlikely to occur unless special initiatives are involved. Other processes, such as carbon black production, have process requirements which make direct substitution of coal highly unlikely.

- Low- or medium-Btu gas from coal is applicable to many processes. Gas from coal has, and is, being used in lime and brick kilns. Other operations, such as alumina calcination, blast furnaces, etc., should also be capable of utilizing gas from coal.

4.1.2 Pollution Potential Profile Analysis

Important conclusions based upon the environmental impacts analysis are:

- Approximately 60 percent of all industrial direct-fired fuel ($4,200 \times 10^{12}$ Btu/year) is fired in processes that emit only products of combustion. The 4.2 quads/year of direct-fired fuel is small in amount compared to the 15 quads/year burned by utility boilers and the 10 quads/year burned in industrial and commercial boilers. Further, direct-fired processes burn mostly gas or oil; therefore, they do not appear to be serious contributors to the national burden of pollution from combustion products. However, actual emission data are limited, and local effects from operations such as refineries or other installations with large fuel consumption may be significant--either for the operations' generation of NO_x and SO_x or because the operations emit products of incomplete combustion.

- The remaining 40 percent of direct-fired fuel ($2,800 \times 10^{12}$ Btu/year) is fired in processes, such as cement kilns and reverberatory furnaces, which permit co-mingling of the combustion products with dust and volatiles evolved by materials charged to the process. Discharges of these process contaminants do not appear to have been fully characterized. For example, copper smelting operations discharge large quantities of dust and SO_x and other contaminants, such as volatile metals. Hydrocarbons, originating from ore flotation agents and introduced with the ore concentrate, are also believed to be present in the off-gases in significant amounts. While it is not known whether hydrocarbons or trace metals such as arsenic and cadmium are present in quantities that constitute an environmental threat, further investigation is felt to be necessary. Also, better knowledge of the content of raw materials being fed to direct-fired processes would be useful in understanding the potential for impacts from such processing.

- Major environmental impacts result from direct firing of fuel in the primary metals industry group, especially in the iron and steel industry. One of the most significant sources of pollution in the iron and steel industry is the coke oven process. Emissions from this process include unburned hydrocarbons and SO_x. Other significant polluting processes in the iron and steel industry are blast furnace pig iron production, steelmaking, and sintering. The emissions from these processes include particulates, volatile metal fumes, CO, and SO_x.

- The most important pollutant resulting from direct-fired processes in the mineral processing industries is fine particulate from cement, lime, and glass production. These particulates are primarily from processed material and are affected only slightly by type of fuel used.

4.2 DATA NEEDS

This section presents data needs which were identified during the analysis of the energy consumption and pollution potential profiles.

4.2.1 Energy Consumption Profile Analysis

Two major industry groups, food and paper, were characterized by a lack of information concerning direct-fired fuel usage. Information could not be found in the literature describing processes using direct-fired energy or equipment which was direct-fired. However, the information which was available indicated that direct-fired energy use is not relatively significant in these industry groups.

The major data need identified in the chemical industry concerned feedstock consumption by organic chemicals. The information which was available was incomplete in many instances. The variety of processes available to produce the same end product and the utilization of some chemicals as intermediate products as well as end products contribute to the lack of information.

Coverage of processes in the chemical industry was the lowest of all industries studied due once again to the diverse nature of the organic chemicals industries, which include plastics and resins, synthetic rubber, olefins, and cyclic intermediates as products.

Information on fuel consumption was available only for the largest and most important chemical products. However, the remaining less important products and processes consume a significant amount of this industry group's energy.

The information available concerning the petroleum refining industry was basically complete. The major problem was that utility requirements, i.e., heat, steam, and electricity, were reported with ranges and an average value. The average values were used, but in some cases the reported ranges

were very wide with few actual data points for averaging. Part of this disparity is caused by the diverse nature of the petroleum refining industry, due in large part to the wide variety of raw materials processed by the various refineries.

Reliable production data for certain primary metals were not available, e.g., beryllium, titanium, and tungsten. This data is withheld to avoid discolosure of individual company confidential data.

4.2.2 Pollution Potential Profile Analysis

Several important data needs were identified concerning pollution potential from direct-fired processes. These data needs are presented below.

A lack of emission factor data for specific direct-fired processes prevented the quantitative evaluation of the environmental impacts associated with these processes. Further work that establishes these emission factors is necessary to determine relative impacts of these processes.

Limited information exists on the nature of emissions from direct-fired processes within certain minor, yet potentially hazardous, industries and within certain widely diversified industries, such as organic chemicals.

Data concerning the effects of fuel switching on emissions provide very little quantitative information. The qualitative nature of this information is due in part to the large number of variables involved in a discussion of alternate fuels. Many of these variables are site-specific and cannot be discussed meaningfully in general terms.

A similar lack of quantitative information exists concerning the environmental impact of new technologies which have not undergone extensive demonstration and testing. This is especially true in instances where there are few, if any, domestic installations utilizing the technology in question.

Conclusions regarding pollution potential of direct-fired processes must be reassessed as more definitive emissions data and emission factor information become available.

4.2.3 General Data Needs

Identification of the specific processes consuming large amounts of direct-fired fuel has established a basis for analysis of possibilities for changing fuel use practices to better deal with energy problems created by dwindling gas supplies and rising oil costs. The background which has been developed can be used to evaluate the nature of the specific energy requirements of greatest importance and thereby determine whether fuel substitution or process substitution would be attractive. Firm conclusions with respect to fuel switching will, however, require thorough engineering studies beyond the scope of this study.

Data collected during this study for other types of industrial energy consumption (process steam, electricity, chemical feedstocks, and metallurgical reductant) could be used for process-specific analysis of the type conducted for direct-fired processes. From past work it appears that a population of a few hundred specific processes which consume 70-80% of all industrial energy could be identified. This information and estimates for the type and amount of energy consumed by each process should provide valuable new perspective useful in further analysis of industrial energy consumption and its environmental consequences.

APPENDIX A

DETAILED ENERGY CONSUMPTION DATA

FOR SIX MAJOR INDUSTRIES

TABLE A-1. ENERGY CONSUMPTION IN SIX MAJOR INDUSTRIES BY RAW MATERIAL, 10^{12} BTU/YR

Raw Material	Industry/Product	SIC	Date	Electricity[4]	Direct-Fired[5]	Process Steam[3,5]	Feedstock[5]	Metallurgical[5] Reductant	Total[1,2]
	FOOD	20							
	Sources: (2,23,24)								
Coffee beans	Coffee	2095	1971	2.60	3.46	4.77	-	-	10.83
Cotton	Cottonseed oil	2074	1971	6.47	-	4.78	-	-	11.25
Grain	Prepared feeds, pet food	2047/ 2048	1971	69.97	23.07	37.16	-	-	130.20
	Wet corn milling	2046	1971	15.26	9.65	44.24	-	-	69.15
	Flour, grain	2041	1971	56.75	2.90	5.59	-	-	65.24
	Baked goods	2051	1971	15.24	21.65	16.25	-	-	53.14
	Soybean oil mills	2075	1971	12.88	9.16	30.09	-	-	52.13
	Malt beverages	2082	1971	12.80	2.03	35.33	-	-	50.17
	Distilled spirits	2085	1971	8.31	0.08	17.55	-	-	25.93
	Blended flour	2045	1971	18.76	-	0.87	-	-	19.63
	Cookies, crackers	2052	1971	3.85	7.71	0.64	-	-	12.21
	Cereal	2043	1971	4.38	2.50	4.03	-	-	10.90
	Malt	2083	1971	2.77	8.11	-	-	-	10.88
	Rice milling	2044	1971	8.87	0.81	0.86	-	-	10.53
	Macaroni	2098	1971	1.36	-	1.54	-	-	2.90
Meat animals	Meat packing	2011	1971	36.96	5.26	67.05	-	-	109.27
	Poultry dressing, processing	2016/ 2017	1971	14.02	0.11	16.61	-	-	30.74
	Sausages, prepared meats	2013	1971	9.46	1.85	14.39	-	-	25.71
Milk	Fluid milk	2026	1971	40.18	2.43	39.29	-	-	81.90
	Cheese	2022	1971	3.96	6.28	12.85	-	-	23.09
	Condensed/evaporated milk	2023	1971	2.44	5.29	15.08	-	-	22.81
	Butter	2021	1971	1.86	2.47	6.64	-	-	10.96
	Ice Cream	2024	1971	5.63	0.03	2.60	-	-	8.26
Seafood	Canned seafood	2091	1971	1.19	-	4.35	-	-	5.54
	Fresh, frozen fish	2092	1971	2.51	-	2.55	-	-	5.06
Sugar crops	Beet sugar	2063	1971	6.14	25.03	52.67	-	-	83.84
	Cane sugar refining	2062	1971	2.28	0.69	32.10	-	-	35.07
	Raw cane sugar	2061	1971	2.19	-	12.59	-	-	14.78
Vegetables, fruits, and nuts	Canned fruits and vegetables	2033	1971	16.57	-	44.16	-	-	60.72
	Frozen fruits, vegetables, and specialties	2037/ 2038	1971	19.95	-	23.99	-	-	43.94
	Dehydrated fruits and vegetables	2034	1971	2.60	-	8.16	-	-	10.75
	Pickled fruits and vegetables	2035	1971	3.01	-	5.78	-	-	8.79
	Vegetable oil	2076	1971	1.66	-	3.41	-	-	5.07
	Wines	2084	1971	1.76	0.16	3.09	-	-	5.01
	Chocolate	2066	1971	2.09	1.54	0.40	-	-	4.03
Other	Animal, marine fats and oils	2077	1971	9.25	0.33	31.09	-	-	40.67
	Soft drinks	2086	1971	10.29	0.90	20.08	-	-	31.27
	Shortening, oil	2079	1971	5.52	-	24.31	-	-	29.83
	Canned specialties	2032	1971	5.81	-	17.85	-	-	23.67
	Confections	2065	1971	9.13	5.06	5.75	-	-	19.94
	Ice	2097	1971	12.29	0.31	-	-	-	12.59
	Flavoring extracts	2087	1971	1.50	6.14	-	-	-	7.65
	Chewing gum	2067	1971	0.52	-	0.87	-	-	1.39

(Continued)

TABLE A-1. ENERGY CONSUMPTION IN SIX MAJOR INDUSTRIES BY RAW MATERIAL, 10^{12} BTU/YR (Continued)

Raw Material	Industry/Product	SIC	Date	Electricity[4]	Direct-Fired[5]	Process Steam[3,5]	Feedstock[5]	Metallurgical[5] Reductant	Total[1,2]
	PAPER	26							
	Sources: (2,4)								
Timber	Paper products	26	1971	634.03	39.75	1,645.82	-	-	2,319.60
	INORGANIC CHEMICALS	28							
	Sources: (2,8,25,26,27,28)								
Air	Oxygen	2813	1975	65.67	-	-	-	-	65.67
	Nitrogen	2813	1975	42.22	-	-	-	-	42.22
	Argon	2813	1975	1.75	0.04	-	-	-	1.79
Arsenic	Arsenic oxide	2819	1973	0.01	0.12	-	-	-	0.13
Barite	Barite	2819	1975	0.58	0.16	-	-	-	0.73
Borax	Borax	2819	1975	0.21	0.79	3.76	-	-	4.76
Chlorine and caustic soda	Chlorine and caustic soda	2812	1973	198.94	-	214.14	-	-	413.08
Lithium	Lithium hydroxide	2819	1975	0.32	2.62	-	-	-	2.94
Mercury	Mercury	2819	1975	0.02	0.06	-	-	-	0.08
Phosphate rock	Phosphorus	2819	1973	71.21	2.54	-	-	17.32	91.07
	Phosphoric acid	2874	1973	11.26	6.81	18.10	-	-	36.16
Potash	Potash	2819	1973	2.65	5.43	4.29	-	-	12.37
Rare earths	Rare earths	2819	1973	0.17	0.13	-	-	-	0.30
Sodium	Sodium salt	2899	1975	0.92	-	12.83	-	-	13.75
	Sodium metal	2819	1975	11.71	-	1.26	-	0.08	13.05
Uranium	Uranium oxide	2819	1975	1.96	2.60	-	-	-	4.56
	ORGANIC CHEMICALS	28							
	Sources: (2,5,29,30,31)								
Oil and gas	Ethylene/propylene	2869	1971	11.91	194.46	174.61	1,079.43	-	1,460.41
	Ammonia	2873	1975	4.79	139.00	125.63	368.29	-	637.70
	Ethylbenzene/styrene	2865	1971	3.97	19.84	27.78	87.31	-	138.90
	Carbon black	2895	1971	-	39.68	-	99.21	-	138.89
	Ethylene oxide	2869	1971	10.17	-	(5.51)	78.03	-	82.69
	Formaldehyde	2869	1971	2.92	-	(3.07)	64.26	-	64.11
	P-xylene	2865	1971	3.71	-	2.64	47.24	-	53.59
	Benzene	2865	1971	2.38	44.83	1.65	-	-	48.86
	Cumene	2865	1971	-	-	8.33	33.73	-	42.06
	Isopropyl alcohol	2869	1971	1.25	-	14.31	24.92	-	40.48
	Polyethylene, low density	2821	1971	34.34	-	5.82	-	-	40.16
	Acetaldehyde	2869	1971	0.39	-	1.99	20.99	-	23.37
	Butadiene	2869	1971	1.57	3.39	17.08	-	-	22.04
	Acrylate esters	2869	1971	0.25	-	6.62	14.86	-	21.73
	Polyvinyl chloride and polymers	2821	1971	5.31	6.90	9.10	-	-	21.31

(Continued)

TABLE A-1. ENERGY CONSUMPTION IN SIX MAJOR INDUSTRIES BY RAW MATERIAL, 10^{12} BTU/YR (Continued)

Raw Material	Industry/Product	SIC	Date	Electricity[6]	Direct-Fired[5]	Process Steam[3,5]	Feedstock[5]	Metallurgical[5] Reductant	Total[1,7]
Oil and gas (con't)	Phenol/acetone	2865/ 2869	1971	1.59		18.65	-	-	20.24
	Caprolactam	2869	1971	0.52	0.21	3.71	11.54	-	15.98
	Methanol	2869	1971	0.19	16.63	(1.01)	-	-	15.81
	Polystyrene and copolymers	2821	1971	8.50	2.56	2.55	-	-	13.61
	Dimethyl terephthalate	2865	1971	5.98	3.90	3.45	-	-	13.33
	Styrene butadiene rubber	2822	1971	5.64	-	7.63	-	-	13.27
	Ethanol	2869	1971	0.89	1.67	9.72	-	-	12.28
	Polyethylene, high density	2821	1971	2.74	-	9.05	-	-	11.79
	Polybutadiene	2822	1971	1.58	-	8.31	-	-	9.89
	α-olefins	2869	1971	0.18	-	1.69	5.23	-	7.10
	Butyl rubber	2822	1971	3.11	0.01	2.45	-	-	5.57
	Chloromethanes	2869	1971	1.57	-	3.77	-	-	5.34
	Maleic anhydride	2865	1971	1.32	-	(2.47)	6.18	-	5.03
	Methylamines	2869	1971	0.17	-	2.36	2.34	-	4.87
	Polyisoprene	2822	1971	0.62	-	2.60	-	-	3.22
	sec-butyl alcohol	2869	1971	0.51	-	2.58	-	-	3.09
	Acrylic acid	2869	1971	0.37	-	0.43	2.28	-	3.08
	Bisphenol A	2865	1971	0.70	-	1.79	-	-	2.49
	Chlorofluoromethanes	2869	1971	1.10	-	1.06	-	-	2.16
	Chloroprene	2822	1971	0.14	-	1.06	-	-	1.20
	PETROLEUM REFINING	29							
	Sources: (2,6,32,33)								
Oil and gas	Atmospheric distillation	2911	1973	32.40	529.30	87.90	-	-	649.60
	Fluid catalytic cracking	2911	1973	41.90	229.20	208.70	-	-	479.80
	Catalytic reforming	2911	1973	21.80	407.10	32.70	-	-	461.60
	Vacuum distillation	2911	1973	17.70	296.50	48.80	-	-	363.00
	Delayed coking	2911	1973	11.70	266.20	33.00	-	-	310.90
	Gas oil hydrotreating	2911	1973	29.60	199.90	14.80	-	-	164.30
	Naphtha hydrotreating	2911	1973	12.30	77.80	12.30	-	-	102.40
	Alkylation	2911	1973	5.20	42.80	43.20	-	-	91.20
	Thermal cracking	2911	1973	1.60	23.40	1.50	-	-	26.50
	Visbreaking	2911	1973	1.20	17.90	3.60	-	-	22.70
	MINERAL PRODUCTS	32							
	Sources: (2,6,8,25,26,27,28)								
Asbestos	Asbestos	3292	1975	0.32	0.17	-	-	-	0.49
Clays	Brick	3251	1973	6.57	52.84	-	-	-	59.40
	Clays	3295	1975	9.33	19.68	-	-	-	29.01
	Fireclay brick	3255	1973	0.64	6.67	-	-	-	7.31
	Basic brick	3297	1973	0.56	3.35	-	-	-	3.90
Diatomite	Diatomite	3295	1975	1.25	3.29	-	-	-	4.54
Feldspar	Feldspar	3295	1975	0.46	0.52	-	-	-	0.99
Graphite	Graphite	3295	1975	0.29	0.08	-	-	-	0.37
Gypsum	Gypsum	3275	1975	2.46	9.18	-	-	-	11.64

(Continued)

TABLE A-1. ENERGY CONSUMPTION IN SIX MAJOR INDUSTRIES BY RAW MATERIAL, 10^{12} BTU/YR (Continued)

Raw Material	Industry/Product	SIC	Date	Electricity[4]	Direct-Fired[5]	Process Steam[3,5]	Feedstock[5]	Metallurgical[5] Reductant	Total[1,2]
Limestone	Cement	3241	1971	105.38	324.50	-	-	-	429.88
	Lime	3274	1975	11.38	145.85	-	-	-	157.24
Mica	Mica (ground)	3295	1973	0.61	0.58	-	-	-	1.19
Perlite	Perlite	3295	1975	0.19	2.47	-	-	-	2.66
Pumice	Pumice	3295	1975	0.25	0.81	-	-	-	1.06
Sand and gravel	Glass	3211/ 3221/ 3229	1973	59.30	258.52	-	-	-	317.82
Talc and soapstone	Talc and soapstone	3295	1975	0.48	0.05	-	-	-	0.53
Vermiculite	Vermiculite	3295	1975	0.38	0.48	-	-	-	0.86
	METALS	33							
	Sources: (2,6,7,8,25,26,27,28)								
Antimony	Antimony	3339	1975	0.01	0.06	-	-	0.17	0.24
Bauxite	Aluminum	3334	1975	663.70	41.93	106.25	-	51.47	863.35
Beryllium ore	Beryllium	3339	1975	0.17	0.11	-	-	-	0.28
Cadmium	Cadmium	3339	1975	0.06	0.10	-	-	-	0.16
Chromite	Low-carbon ferrochromium	3313	1975	4.74	0.07	-	-	1.61	6.42
	High-carbon ferrochromium	3313	1975	4.52	0.08	-	-	1.39	5.99
Copper ore	Copper	3331	1975	63.34	58.03	(5.81)	-	-	115.56
Gold	Gold	3339	1975	0.47	0.13	-	-	-	0.61
Iron ore	Iron and steel	331/ 332	1975	370.60	1,145.07	127.78	-	1,264.25	2,907.71
Lead ore	Lead	3332	1975	1.73	3.55	-	-	4.71	9.99
Magnesium	Magnesium	3339	1973	25.33	16.23	-	-	0.55	42.11
Manganese ore	Ferromanganese	3312/ 3313	1975	7.63	3.03	0.38	-	18.26	29.30
Molybdenum ore	Molybdenum	3313	1975	0.73	0.20	-	-	-	0.93
Nickel ore	Nickel	3339	1975	0.42	0.63	(0.20)	-	0.06	0.91
Silicon ore	Ferrosilicon	3313	1975	26.18	7.15	0.04	-	1.57	34.95
Silver ore	Silver	3339	1975	0.82	0.84	0.45	-	-	2.11
Tin ore	Tin	3339	1973	0.10	0.69	-	-	0.21	1.01
Titanium ore	Titanium	3339	1973	21.39	18.17	11.61	-	5.94	57.11
Tungsten ore	Tungsten	3356	1975	0.25	0.27	-	-	-	0.52

(Continued)

TABLE A-1. ENERGY CONSUMPTION IN SIX MAJOR INDUSTRIES BY RAW MATERIAL, 10^{12} BTU/YR (Continued)

Raw Material	Industry/Product	SIC	Date	Electricity[4]	Direct-Fired[5]	Process Steam[3,5]	Feedstock[5]	Metallurgical Reductant	Total[1,2]
Vanadium ore	Ferrovanadium	3313	1973	0.18	1.20	-	-	-	1.38
Zinc ore	Zinc	3333	1975	16.26	2.86	-	-	3.29	22.42
Zirconium ore	Zirconium	3339	1973	1.32	0.17	-	-	0.04	1.53

[1]Numbers may not add to totals due to independent rounding.
[2]Estimates exclude "non-process" energy (for lighting, HVAC systems, transportation, etc.) where possible.
[3]Steam credits are indicated by numbers in parentheses.
[4]Purchased and self-generated electricity are converted at 10,500 Btu/Kwh.
[5]Energy conversions (Btu/lb, Btu/ft^3, etc.) are as used by data sources (See References).

TABLE A-2. ENERGY CONSUMPTION IN DIRECT-FIRED PROCESSES IN SIX MAJOR INDUSTRY GROUPS

Raw Material	SIC	Industry	Process	10^{12} Btu/yr
Grain	2047/2048	Prepared feeds/pet foods	Drying	23.07
	2051	Baked goods	Baking	18.04
	2046	Wet corn milling	Drying	9.65
	2075	Soybean oil mills	Drying	9.16
	2083	Malt	Heating/drying	8.11
	2052	Cookies, crackers	Baking	7.71
	2041	Flour/grain	Drying	2.90
	2043	Cereal	Drying	2.50
	2051	Baked goods	Water heating	2.41
	2082	Malt beverages	Drying	2.03
	2051	Baked goods	Frying	1.20
	2044	Rice milling	Drying	0.81
	2085	Distilled spirits	Barrel charring	0.08
Sugar crops	2063	Beet sugar	Drying	21.78
		Beet sugar	CO_2 production	3.25
	2062	Cane sugar refining	Refining	0.69
Milk	2022	Cheese	Drying	6.28
	2023	Condensed/evaporated milk	Drying	5.29
	2021	Butter	Drying	2.47
	2026	Fluid milk	Drying	2.43
	2024	Ice cream	Drying	0.03
Meat animals	2011	Meat packing	Smoking/cooking	2.25
		Meat packing	Afterburning	1.50
		Meat packing	Hair removal	1.50
	2013	Sausages and prepared meats	Baking/smoking	1.04
	2013	Sausages and prepared meats	Afterburning	0.70
	2013	Sausages and prepared meats	Cooking	0.12
	2016/2017	Poultry dressing/processing	Water heating	0.11
Coffee beans	2095	Coffee	Roasting	2.21
	2095	Coffee	Drying	1.26
Vegetables, fruits, nuts	2066	Chocolate	Roasting	1.54
	2084	Wines	Drying	0.16
Other	2087	Flavoring extracts	Evaporation	6.14
	2065	Confections	Roasting	3.10
	2065	Confections	Cooking	1.97
	2086	Soft drinks	Can washing	0.90
	2077	Animal/marine fats	Water heating	0.33
	2097	Ice	Water heating	0.31
Timber	26	Coated paper	Drying	26.88
	26	Pulp	White liquor production	12.87
Phosphate rock	2874	Phosphoric acid	Drying	6.81
	2819	Phosphorus	Ore nodulizing	2.54
Potash	2819	Potash	Drying	2.23
		Potash	Leaching	2.14
		Potash	Granulating	1.06
Lithium	2819	Lithium hydroxide	Calcining	2.62
Uranium	2819	Uranium oxide	Drying/calcining	1.45
	2819	Uranium oxide	Leaching	1.15
Borax	2819	Borax	Drying	0.79
Barite	2819	Barite	Drying	0.16
Rare earths	2819	Rare earths	Drying/calcining	0.13
Arsenic	2819	Arsenic oxide	Roasting	0.12
Mercury	2819	Mercury	Ore roasting	0.06
Air	2813	Argon	O_2 burnout	0.04

(Continued)

TABLE A-2. ENERGY CONSUMPTION IN DIRECT-FIRED PROCESSES IN SIX MAJOR INDUSTRY GROUPS (Continued)

Raw Material	SIC	Industry/Product	Process	10^{12} Btu/yr
Oil and gas	2869	Ethylene/propylene	Naphtha cracking	194.46
	2873	Ammonia	Steam-hydrocarbon reforming	139.00
	2865	Benzene	Shell sulfolane	44.83
	2895	Carbon black	Furnace black	35.71
	2865	Ethylbenzene/styrene	Superheater	19.84
	2869	Methanol	ICI low pressure	16.63
	2821	PVC and copolymers	Drying	6.90
	2895	Carbon black	Drying	3.97
	2865	Dimethyl terephthalate	Dynamit Nobel	3.90
	2869	Butadiene	Naphtha cracking	3.39
	2821	Polystyrene and copolymers	Continuous mass polymerization	2.56
	2869	Ethanol	Veba-Chemie	1.67
	2869	Caprolactam	DSM low sulfate	0.21
	2822	Butyl rubber	Drying	0.01
Oil and gas	2911	Petroleum refining	Atmospheric distillation	529.30
			Catalytic reforming	407.10
			Vacuum distillation	296.50
			Delayed coking	266.20
			Fluid catalytic cracking	229.20
			Gas oil hydrotreating	119.90
			Naphtha hydrotreating	77.80
			Alkylation	42.80
			Thermal cracking	23.40
			Visbreaking	17.90
Limestone	3241	Cement	Clinker burning	324.50
	3274	Lime	Calcination	145.85
Sand and gravel	3211/	Glass	Melting	227.18
	3221/		Annealing	25.57
	3229		Forming	5.76
Clays	3251	Brick	Drying/firing	52.84
	3295	Clays	Drying	19.68
	3255	Fireclay brick	Drying	6.67
	3297	Basic brick	Curing/drying/firing	2.46
			Pitch heating	0.84
			Pitch impregnation	0.05
Gypsum	3275	Gypsum	Calcination	7.83
			Drying	1.35
Diatomite	3295	Diatomite	Drying	2.22
			Calcination	1.07
Perlite	3295	Perlite	Heat expansion	2.47
Pumice	3295	Pumice	Drying	0.81
Mica	3295	Ground mica	Drying	0.58
Feldspar	3295	Feldspar	Drying	0.52
Vermiculite	3295	Vermiculite	Exfoliation	0.48
Asbestos	3292	Asbestos	Drying	0.17
Graphite	3295	Graphite	Drying	0.08
Talc and soapstone	3295	Talc, soapstone	Drying	0.05
Iron ore	331/332	Iron and steel	Slabbing	427.80
			Pig iron production	267.27
			Coke production	144.77
			Heat treatment	111.52
			Steelmaking	88.43
			Cast iron and steel melting	39.44
			Pelletizing	26.45
			Core molding	20.40
			Casting	10.08
			Afterburning	5.05
			Sintering	4.87

(Continued)

TABLE A-2. ENERGY CONSUMPTION IN DIRECT-FIRED PROCESSES IN SIX MAJOR INDUSTRY GROUPS (Continued)

Raw Material	SIC	Industry/Product	Process	10^{12} Btu/yr
Copper ore	3331	Copper	Smelting	34.66
			Refining	11.28
			Flotation	3.91
			Cathode melting	2.70
			Acid plant	2.18
			Roasting	2.01
			Converting	1.29
Bauxite	3334	Aluminum	Calcination	29.95
			Carbon anode baking	11.97
Titanium ore	3339	Titanium	Calcination	17.60
			Drying	0.20
			Chlorination	0.17
			Reduction	0.08
			Distillation/purification	0.08
			Leaching	0.03
			Oxidation	0.01
Magnesium	3339	Magnesium	Drying	4.09
			Evaporation	4.08
			Electrolysis	2.85
			Calcination	1.80
			Purification	1.69
			Acid plant	1.40
			Electrode manufacturing	0.31
Silicon ore	3313	Ferrosilicon	Smelting	7.15
Lead ore	3332	Lead	Drossing	0.78
			Debismuthing	0.71
			Sintering	0.55
			Refining	0.53
			Acid production	0.38
			Desilverizing	0.33
			Dezincing	0.15
			Smelting	0.12
			Retorting	0.01
Manganese ore	3312/3313	Ferromanganese	Smelting	3.03
Zinc ore	3333	Zinc	Sintering	1.95
			Roasting	0.48
			Reduction	0.26
			Drying	0.15
			Acid plant	0.02
Vanadium ore	3313	Ferrovanadium	Roasting	0.77
			Precipitation	0.18
			Drying	0.11
			Solvent extraction	0.10
			Leaching	0.04
			Smelting	0.01
			Electrode manufacturing	0.01
Silver ore	3339	Silver	Refining	0.50
			Roasting	0.16
			Leaching	0.16
			Melting/casting	0.02
Tin ore	3339	Tin	Smelting	0.35
			Refining	0.35
Nickel ore	3339	Nickel	Smelting	0.61
			Reduction	0.02
Tungsten ore	3313	Tungsten	Reduction	0.27
Molybdenum ore	3313	Molybdenum	Roasting	0.20
Chromite	3313	Ferrochromium	Smelting	0.15
Gold	3339	Gold	Leaching	0.11
			Melting	0.02

(Continued)

TABLE A-2. ENERGY CONSUMPTION IN DIRECT-FIRED PROCESSES IN SIX MAJOR INDUSTRY GROUPS (Continued)

Raw material	SIC	Industry/Product	Process	10^{12} Btu/yr
Zirconium ore	3339	Zirconium	Filtration/calcination	0.15
			Drying	0.02
			Chlorination	0.01
Beryllium ore	3339	Beryllium	Precipitation	0.03
			Leaching	0.03
			Partial dehydration	0.03
			Sintering	0.02
			Filtration	0.01
Cadmium	3339	Cadmium	Roasting	0.10
			Melting	0.01
Antimony	3339	Antimony	Refining	0.05
			Reducing	0.01
			Converting	0.01

TABLE A-3. DIRECT-FIRED PROCESS EQUIPMENT

Industry Group/SIC	Equipment	Process	Raw Material/Product	10^{12} Btu/yr
Food/20	Lime kiln	CO_2 production	Beet sugar	3.25
	Char kiln	Charring	Cane sugar refining	0.69
	Kiln	Barley heating and drying	Malt	8.11
	Afterburner	Firing of unburned fuel	Meat packing	1.50
	Afterburner	Firing of unburned fuel	Sausages, prepared meats	0.70
	Data not available (DNA)	Barrel charring	Distilled spirits	0.08
	Dryer	Drying	Prepared feeds	23.07
	Dryer	Drying	Soybean oil	9.16
	Drying kiln	Drying	Milk	2.43
	Drying furnace	Drying	Beet sugar	21.78
	Dryer furnace	Drying	Wet corn milling	9.64
	Drying oven	Drying	Cereal	2.50
	Oven	Smoking/cooking	Meat packing	2.25
	Oven	Baking	Baked goods	18.04
	Oven	Baking	Cookies, crackers	7.71
	Oven/smokehouse	Cooking/smoking	Sausage, prepared meats	1.04
	Fryer	Frying	Baked goods	1.20
	Hot water heater	Water heating	Baked goods	2.41
	Hot water heater	Water heating	Animal, marine fats	0.33
	Hot water heater	Water heating	Poultry dressing	0.11
	Hot water heater	Water heating	Ice	0.31
	Cooker	Cooking	Sausage, prepared meats	0.12
	Gas singer	Hair removal	Meat packing	1.50
	Dryers, various	Drying	Flour, grain	2.90
	Dryers, various	Drying	Malt beverages	2.03
	Dryers, various	Drying	Cheese	6.28
	Dryers, various	Drying	Condensed, evaporated milk	5.29
	Dryers, various	Drying	Coffee	1.26
	Dryers, various	Drying	Butter	2.47
	Dryers, various	Drying	Rice milling	0.81
	Dryers, various	Drying	Ice cream	0.03
	Dryers, various	Pomace drying	Wines	0.16
	Can washer	Can washing	Soft drinks	0.90
	Roasters, various	Roasting	Confections	3.10
	Roasters, various	Roasting	Coffee	2.21
	Roasters, various	Roasting	Chocolate	1.54
	DNA	Cooking	Confections	1.96
	Evaporators	Evaporation, dehydration	Flavoring extracts	6.14
Paper/26	Rotary lime kiln	White liquor production	Pulp	12.87
	Gas-fired infra-red burner	Drying	Coated paper	26.88

(Continued)

TABLE A-3. DIRECT-FIRED PROCESS EQUIPMENT (Continued)

Industry Group/SIC	Equipment	Process	Raw Material/Product	10^{12} Btu/yr
Chemicals/28	Tubular preheater	Naphtha cracking	Ethylene/propylene	194.46
	Tubular preheater	Naphtha cracking	Butadiene	3.39
	Tubular preheater	Veba Chemic	Ethanol	1.67
	Tubular preheater	Shell Sulfolane	Benzene	44.83
	Tubular preheater	Dynamit Nobel	Dimethyl terephthalate	3.90
	Oil furnace	Furnace black	Carbon black	35.71
	Fired steam superheater	Monsanta	Ethylbenzene/styrene	19.84
	Tubular furnace	Steam-hydrocarbon reforming	Ammonia	139.00
	Kiln (rotary)	Ore nodulizing	Phosphorus	2.54
	Kiln (rotary)	Drying, calcination	Uranium oxide	1.45
	Kiln (rotary)	Calcination	Lithium hydroxide	2.62
	Kiln (rotary)	Ore roasting	Mercury	0.02
	Dryer (rotary)	Concentrate drying	Phosphoric acid	6.81
	Dryer (rotary)	Drying	Carbon black	3.97
	Dryer (rotary)	Potash drying	Potash	2.23
	Dryer (rotary)	Borax drying	Borax	0.40
	Dryer (rotary)	Drying	Synthetic rubber-butyl	0.01
	Dryer (spray)	Drying	PVC and copolymers	6.90
	Dryer (tray)	Borax drying	Borax	0.39
	Dryer	Drying	Barite	0.16
	Dryer	Drying, calcination	Rare earths	0.13
	Autoclave	Leaching	Uranium oxide	1.15
	Catalytic combustion furnace	O_2 burnout (purification)	Argon	0.04
	Roaster	Precipitate roasting	Arsenic oxide	0.12
	Roaster (multiple hearth)	Ore roasting	Mercury	0.02
	Retort furnace	Ore roasting	Mercury	0.02
	DNA	Leaching	Potash	2.14
	DNA	Granulating	Potash	1.06
	Various	DSM low sulfate	Caprolactam	0.21
	Various	Continuous mass polymerization	Polystyrene and copolymers	2.56
	Various	ICI low pressure	Methanol	16.63
Petroleum/29	Tubular preheater	Atmospheric distillation	Oil and gas	529.30
	Tubular preheater	Vacuum distillation	Oil and gas	296.50
	Tubular preheater	Thermal cracking	Oil and gas	23.40

(Continued)

TABLE A-3. DIRECT-FIRED PROCESS EQUIPMENT (Continued)

Industry Group/SIC	Equipment	Process	Raw Material/Product	10^{12} Btu/yr
	Tubular preheater	Fluid catalytic cracking	Oil and gas	229.20
	Tubular preheater	Catalytic reforming	Oil and gas	407.10
	Tubular preheater	Naphtha hydrotreating	Oil and gas	77.80
	Tubular preheater	Gas oil hydrotreating	Oil and gas	119.90
	Visbreaking furnace	Visbreaking	Oil and gas	17.90
	Refinery delayed coking unit	Delayed coking	Oil and gas	266.20
	Reboiler furnace	Alkylation	Oil and gas	42.80
Stone/Clay/ Glass/Concrete/ 32	Kiln (rotary)	Clinker burning	Cement	324.50
	Kiln (rotary)	Calcination	Lime	116.68
	Kiln (rotary)	Calcination	Gypsum	3.91
	Kiln (rotary)	Calcination	Diatomite	1.07
	Kiln (vertical shaft)	Calcination	Lime	29.17
	Kiln (tunnel)	Drying, firing	Brick	34.34
	Kiln (tunnel)	Drying, firing	Fireclay brick	3.34
	Kiln (tunnel)	Curing, drying, firing	Basic brick	0.82
	Kiln (periodic)	Drying, firing	Brick	18.49
	Kiln (periodic)	Drying, firing	Fireclay brick	3.34
	Kiln (periodic)	Curing, drying, firing	Basic brick	0.82
	Kiln (gypsum pot)	Calcination	Gypsum	3.91
	Reverberatory furnace	Melting, firing, conditioning	Glass	227.18
	Lehr (tunnel oven)	Annealing	Glass	25.57
	Impregnation unit	Pitch impregnation	Basic brick	0.05
	Hammer mill-hot blower	Drying	Diatomite	2.22
	Furnace (stationary, vertical)	Heat expansion	Perlite	0.82
	Furnace (vertical)	Exfoliation	Vermiculite	0.48
	Furnace (stationary, horizontal)	Heat expansion	Perlite	0.82
	Furnace (rotary, horizontal)	Heat expansion	Perlite	0.82
	DNA	Forming	Glass	5.77
	Dryer (rotary)	Drying	Clays	19.68
	Dryer (rotary)	Drying	Gypsum	1.35
	Dryer (rotary)	Drying	Pumice	0.81
	Dryer (rotary)	Drying	Mica (ground)	0.58
	Dryer (rotary)	Drying	Feldspar	0.52
	Dryer (rotary)	Drying	Talc and soapstone	0.02
	Dryer (tunnel)	Drying	Basic brick	0.82
	Dryer (flash)	Drying	Talc and soapstone	0.02

(Continued)

TABLE A-3. DIRECT-FIRED PROCESS EQUIPMENT (Continued)

Industry Group/SIC	Equipment	Process	Raw Material/Product	10^{12} Btu/yr
	Dryer (vertical)	Drying	Asbestos	0.17
	Dryer	Drying	Graphite	0.08
	Heater	Pitch heating	Basic brick	0.84
Metals/33	Pellet furnace (shaft, traveling grate, rotary kiln, grate-kiln)	Pelletizing	Iron and steel	26.45
	Traveling grate furnace	Sintering	Lead	0.55
	Sintering machine (traveling grace, furnace downdraft)	Sintering	Iron and steel	4.87
	Sintering machine (moving grate, downdraft)	Sintering	Zinc	1.95
	Coke oven (by-product, bee-hive)	Coke production	Iron and steel	144.77
	Blast (shaft) furnace (includes blast stove)	Pig iron production	Iron and steel	267.27
	Blast furnace	Smelting	Ferromanganese	2.70
	Blast furnace	Smelting	Lead	0.12
	Blast furnace	Smelting	Tin	0.35
	Reverberatory furnace	Cathode melting	Copper	2.70
	Reverberatory furnace	Anode melting	Copper	2.52
	Reverberatory furnace (open hearth)	Steelmaking	Iron and steel	71.80
	Reverberatory furnace	Smelting	Copper	34.66
	Reverberatory furnace	Drossing	Lead	0.39
	Reverberatory furnace	Refining	Lead	0.41
	Reverberatory furnace	Refining	Silver	0.50
	Reverberatory furnace	Refining	Tin	0.34
	Reverberatory furnace	Smelting	Nickel	0.61
	Reverberatory furnace	Reducing	Nickel	0.02
	Reverberatory furnace	Refining	Antimony	0.05
	Reverberatory furnace	Reducing	Antimony	0.01
	Furnace (basic oxygen)	Steelmaking	Iron and steel	14.36
	Electric arc furnace	Steelmaking	Iron and steel	2.27
	Induction furnace	Cast iron melting	Iron and steel	16.12
	Electric arc furnace	Cast steel melting	Iron and steel	0.61
	Furnace	Electrolytic refining	Copper	6.25
	Tubular preheating furnace	Electrolysis	Magnesium	2.85
	Electric (submerged) arc furnace	Smelting	Ferrosilicon	7.15
	Electric (submerged) arc furnace	Smelting	Ferromanganese	0.33
	Electric (submerged) arc furnace	Smelting	Low-carbon ferrochromium	0.07
	Electric (submerged) arc furnace	Smelting	High-carbon ferrochromium	0.08
	Electric arc furnace	Smelting	Ferrovanadium	0.01

(Continued)

TABLE A-3. DIRECT-FIRED PROCESS EQUIPMENT (Continued)

Industry Group/SIC	Equipment	Process	Raw Material/Product	10^{12} Btu/yr
	Furnace (soaking pit)	Slabbing, blooming	Iron and steel	156.33
	Reheating furnace	Slabbing, blooming	Iron and steel	271.47
	Reheating furnace	Continuous casting	Iron and steel	3.42
	Heat treating furnace	Heat treatment	Iron and steel	111.52
	Cupola furnace	Cast iron melting	Iron and steel	21.71
	Core oven	Molding/core-making	Iron and steel	20.40
	Afterburner	Air pollution control	Iron and steel	5.05
	Kiln (rotary)	Calcination	Aluminum	29.95
	Kiln (rotary)	Roasting, drying	Copper	1.01
	Kiln (rotary)	Calcination	Titanium	17.60
	Kiln (rotary)	Calcination	Magnesium	1.80
	Kiln (rotary)	Roasting	Molybdenum	0.10
	Furnace (pit)	Carbon anode baking	Aluminum	11.99
	Roaster (multiple hearth)	Roasting, drying	Copper	0.50
	Roaster (multiple hearth)	Roasting	Cadmium	0.05
	Roaster (fluidized-bed	Roasting, drying	Copper	0.50
	Roaster (multiple hearth, fluidized-bed)	Roasting	Zinc	0.48
	Roaster	Roasting	Ferrovanadium	0.76
	Roaster (fluidized-bed)	Roasting	Cadmium	0.05
	Converter	Converting	Copper	1.29
	Furnace (converting)	Converting	Antimony	0.01
	Furnace (rotary)	Anode refining	Copper	2.52
	Flotation cells	Flotation	Copper	3.91
	Reactor furnace	Reduction, sintering	Titanium	0.08
	Dryer	Drying	Titanium	0.20
	Dryer (shelf)	Drying	Magnesium	4.08
	Dryer (rotary)	Drying	Zinc	0.15
	Dryer (rotary)	Drying	Ferrovanadium	0.11
	Furnace (batch, shaft)	Chlorination	Titanium	0.17
	Reaction chamber	Oxidation	Titanium	0.01
	Neutralization tanks	Neutralization, purification	Magnesium	1.69
	Submerged combustion evaporator	Evaporation	Magnesium	4.08
	Furnace (retort)	Reduction	Zinc	0.26
	Furnace (retort)	Retorting	Lead	0.01
	Furnace (retort)	Vacuum dezincing	Lead	0.15

(Continued)

TABLE A-3. DIRECT-FIRED PROCESS EQUIPMENT (Continued)

Industry Group/SIC	Equipment	Process	Raw Material/Product	10^{12} Btu/yr
	Furnace (retort)	Debismuthizing	Lead	0.71
	Furnace (retort)	Refining	Lead	0.12
	Furnace (pot)	Drossing	Lead	0.39
	Furnace (pot)	Desilverizing	Lead	0.33
	Reactor (batch, fluidized-bed)	Chlorination	Zirconium	0.01
	Furnace (multiple hearth)	Roasting	Molybdenum	0.10
	Furnace (dore)	Melting	Gold	0.02
	Furnace (continuous tube)	Reduction	Tungsten	0.27
	DNA	Casting/shakeout/ cleaning	Iron and steel	6.66
	DNA	Acid plant	Copper	2.18
	DNA	Acid plant	Magnesium	1.40
	DNA	Acid production	Zinc	0.02
	DNA	Acid production	Lead	0.38
	DNA	Distillation purification	Titanium	0.08
	DNA	Leaching	Titanium	0.02
	DNA	Leaching	Silver	0.16
	DNA	Leaching	Ferrovanadium	0.04
	DNA	Leaching	Gold	0.11
	DNA	Leaching	Beryllium	0.03
	DNA	Graphite electrode manufacture	Magnesium	0.31
	DNA	Graphite electrode manufacture	Ferrovanadium	0.01
	Roaster	Roasting	Silver	0.16
	DNA	Electric melting and casting	Silver	0.02
	DNA	Melting and casting	Cadmium	0.01
	Dryer	Drying, calcination	Zirconium	0.02
	DNA	Repulping, filtration, calcination	Zirconium	0.15
	DNA	Solvent extraction	Ferrovanadium	0.10
	DNA	Precipitation, filtration, fusion	Ferrovanadium	0.18
	DNA	Sintering	Beryllium	0.02
	DNA	Precipitation	Beryllium	0.03
	DNA	Filtration	Beryllium	0.01
	DNA	Partial dehydration	Beryllium	0.03

APPENDIX B

METHODOLOGY

SECTION 1

ENERGY END USE BASED UPON INDUSTRY-WIDE FUEL USE ESTIMATES

The energy consumption values presented in Table 13 were obtained by taking the total amount of each type of fuel, i.e., coal, gas, oil, and other, consumed by each industry group and proportioning the fuel among the various end uses, i.e., direct firing, process steam, metallurgical reductant, feedstocks, and self-generated electricity. Estimates of purchased electricity consumption were obtained from Census data (2,3). These overall industry values represent the estimated end uses of all fuels consumed, with no consideration given to the energy consumption by specific processes.

The general technique followed in this analysis is presented in Section 1.1. Specific problems encountered in analysis of the six major industry groups are discussed in Section 1.2.

1.1 GENERAL APPROACH

Initially, consumption of all input fuels and purchased elctricity by each 2-digit industry group was estimated. These input energy forms were classified by type, i.e., distillate, oil, residual oil, natural gas, coal, coke, natural gas, purchased electricity, and other fuels. For all industry groups, purchased electricity and purchased fuel data were obtained from Census data (2,3). For the paper, chemicals, petroleum, and primary metals industry groups, estimates of by-product, feedstock, and captive energy consumption were based upon other sources (2,3,4,5,6,7,8,13,14). The energy forms were converted to Btu equivalents and summed to obtain total annual energy consumption estimates for each industry group.

Next, each industry group's self-generated electricity consumption was obtained from Census (2,3) data, converted to Btu equivalents (1 kWh = 10,500 Btu), and added to the group's purchased electricity energy consumption.

Estimates of energy consumed in the production of steam (excluding that amount raised to generate on-site electricity) were based upon Institute of Gas Technology data (9). In this IGT study, boiler energy consumption was given in terms of the percentage consumption of each fuel type (oil, gas, and coal) that specific industries fired in industrial boilers. From these boiler input energy estimates, self-generated electricity energy values were subtracted to yield the amount of energy allocated to process steam production.

Finally, direct-fired energy consumption estimates were obtained by subtracting from the total energy consumption estimates the value of the other energy forms, i.e., purchased electricity, self-generated steam, and feedstocks, by-product fuels, and captive fuels where applicable.

1.2 SPECIFIC INDUSTRY GROUPS

The following sections describe specific methods used in deriving energy end use data for the food, paper, chemicals, petroleum, stone/clay/glass, and primary metals industry groups.

1.2.1 Food and Stone/Clay/Glass

Energy consumption estimates for the food and stone/clay/glass industry groups were obtained from Census data (2,3) and Institute of Gas Technology estimates (9). Since no by-product or captive fuel sources are found in these industry groups, the techniques for estimating end use of energy consumption follows directly from the discussion in Section 1.1.

1.2.2 Paper

Estimates of the paper industry's total energy consumption were based upon Census data for purchased fuels and electricity and American Paper Institute data (4) for by-product fuel consumption.

Electrical energy consumption (purchased and self-generated) estimates are from Census data. It was assumed that by-product fuels were fired in boilers, in addition to the various amounts of coal, oil, and gas indicated in the IGT study. Direct-fired energy consumption values were obtained by difference, as explained in Section 1.1.

1.2.3 Chemicals

Total energy consumption in 1977 by the chemicals industry group was estimated from purchased fuels and electricity consumption as reported in Census data and captive feedstock energy consumption as reported by Shell (5). An estimate of 1971 feedstock energy consumption was obtained by multiplying the 1977 feedstock energy value by an organic chemicals production factor. This factor was defined as the ratio of 1970 and 1976 organic chemical production tonnages, which were obtained from U.S. Tariff Commission and U.S. Trade Commission data (13,14).

Electricity consumption (purchased and self-generated) was obtained from Census data, and estimates of energy consumed for steam production were based upon the IGT boiler data. Energy for direct firing was obtained by subtracting feedstock, electricity, and steam energy from the total energy consumption.

1.2.4 Petroleum

Census data for purchased fuels and electricity and Conference Board estimates (6) of captive fuel consumption were used to obtain total energy

consumption values by the petroleum refining industry. The captive fuel consists of "make gas", fuel oil, petroleum coke, and acid sludge.

Electrical consumption was obtained from Census data. Amounts of coal and purchased and captive fuel oil and gas fired in boilers were allocated according to the IGT percentages. Direct-fired energy values were obtained by difference.

1.2.5 Primary Metals

Census, American Iron and Steel Institute (7), and Battelle (8) information was used to estimate annual energy consumption by the primary metals group. Captive coal consumption by the iron and steel industry was estimated from the AISI publication. Nonferrous captive coal consumption values, e.g., in the aluminum industry, were obtained assuming that an amount of energy equal to approximately 20 percent of the electrical energy consumed by the aluminum industry was representative of the amount of nonferrous captive coal energy consumed. This percentage was based upon information in Battelle. Nonferrous purchased coal energy was obtained from Census data. All other energy derived from purchased fuels and electricity was calculated from Census data and added to the coal energy to yield total energy consumption by the primary metals group.

Purchased and self-generated electricity values were obtained from Census data. The amount of coal assigned to the metallurgical reductant category was determined from AISI data and nonferrous coke consumption data as reported by the Census. Estimates of energy consumed for steam production were based upon AISI data for the iron and steel industry's use of coal in boilers and upon IGT percentages of fuel oil, gas, and remaining coal (in the nonferrous industries) fired in boilers. The amount of direct-fired energy consumption by the primary metals group was obtained by subtracting from the total energy values the amounts of energy assigned to electricity, steam, and metallurgical reductant.

1.2.6 Other

Energy consumption by the other 2-digit manufacturing industry groups was allocated to electrical, steam, and direct-fired use. Total energy input data was obtained from Census information.

Purchased and self-generated electricity consumption values were based upon Census estimates. The IGT boiler percentages were used to determine the amounts of coal, oil, and gas energy consumed in boilers, and the energy assigned to self-generated electricity was subtracted to yield the energy required to raise steam. The energy allocated to direct firing was obtained by subtracting the electrical and steam production energy from the total energy consumption values for 1971 and 1977.

SECTION 2

ENERGY END USE BASED UPON PROCESS-SPECIFIC ENERGY CONSUMPTION ESTIMATES

The energy consumption values in Tables 14, A-1, and A-2 represent the energy accounted for in the six major industry groups on a process-specific basis. In general, the technique used in the development of this data included estimating energy consumption by individual processes. However, estimates of energy consumption by the food and paper industry groups were obtained using overall industry group energy consumption values. These methods are detailed in later sections. Section 2.1 presents the overall approach followed in the development of the data. Section 2.2 outlines analysis of each major industry group.

2.1 GENERAL APPROACH

Various industrial energy consumption studies were consulted so as to classify energy consumption as electrical, steam, direct-fired, metallurgical reductant, or feedstock. Fuel and electrical energy consumption estimates were obtained and tabulated on a process-specific basis for each of the industry groups, except for the paper industry. Energy consumption estimates for major, if not all, processes within each industry group are represented in Table 14.

2.2 SPECIFIC INDUSTRY GROUPS

The following sections explain the methods used in obtaining process-specific energy consumption values for the food, paper, chemicals, petroleum, stone/clay/glass, and primary metals industry groups.

2.2.1 Food

The amount of purchased fuel energy for each 4-digit food industry in the food industry group was obtained from Census data (2). The fraction of each 4-digit industry's total energy consumption (including electricity) represented by purchased fuel energy was estimated from Sittig data (23). The amount of total energy consumption by each 4-digit industry was therefore obtained by dividing purchased fuel energy by the fraction obtained from Sittig.

The direct-fired energy values for each 4-digit industry were obtained by multiplying the total energy consumption of that industry by the percentage used for direct firing, according to Sittig. This energy was then allocated to the various direct-fired processes, again using percentages supplied by Sittig.

Estimates of energy required for steam production, excluding that amount used for on-site electrical generation, were obtained by multiplying each 4-digit industry's total energy consumption by process steam percentages reported by Sittig.

Electrical energy consumption values were obtained by adding estimates of purchased electrical energy and self-generated electrical energy. The purchased electricity values resulted from the difference between total energy consumption and purchased fuel energy consumption. Self-generated electricity energy estimates were obtained by multiplying the boiler input energy values by Sittig's percentages that allocate the amount of boiler input energy used for on-site electricity generation.

All energy consumption estimates include only "process" energy, excluding energy for lighting, transportation, harvesting, HVAC systems, etc.

2.2.2 Paper

Estimates of energy consumption by the paper industry group were based upon data reported by the Census, the American Paper Institute, and industrial contacts. Total energy consumption by the paper industry in 1971 was obtained by adding purchased fuel and electrical energy values (2) to an estimate of by-product fuel energy consumption (4).

Two major direct-fired processes were identified -- drying (gas-fired infrared burners) and burning of lime for white liquor production (lime kilns). Energy consumption values for these processes were based upon information supplied by industrial contacts. Estimates are based upon "average" lime kiln ratings (Btu/ton of lime) and typical burner heat ratings (Btu/hr-inch of burner).

Electrical energy consumption estimates are from Census data, with purchased and self-generated electricity converted at 10,500 Btu/kWh. An industry-wide steam energy value was obtained by subtracting electrical and direct-fired energy estimates from the total energy consumption figure.

Because estimates of steam and electrical energy consumption are based upon total fuel and electricity consumption, these two categories may reflect energy consumed for "non-process" purposes, i.e., lighting, transportation, HVAC systems, etc. This inconsistency results from the lack of information that would yield reliable estimates of process-specific energy consumption. In addition, this lack of a general data base prevented analysis of the paper industry group on a 4-digit industry-by-industry basis. However, the entire paper industry is highly dependent on steam and electricity for process energy, so the lack of process-specific information does not significantly affect this study's analysis of direct-fired processes and equipment.

2.2.3 Chemicals

Process-specific energy consumption estimates are based upon Battelle (8,25,26), Dow (43), and Shell (5) information. These estimates were obtained by multiplying process energy consumption data (in terms of Btu/ton of product) by production tonnages, which were available from several sources (29,30,31,47). The energy was assigned to direct-fired, steam (which includes "negative" values for steam credits), electricity, and feedstock categories. The direct-fired energy was further allocated to specific processes.

In general, estimates of energy consumption by the organic chemical industry are based upon 1971 production data. Inorganic chemical energy consumption values reflect 1973 and 1975 production levels.

"Process" energy includes pollution control energy, but it excludes energy for mining, transportation, lighting, HVAC systems, etc.

2.2.4 Petroleum

Energy consumption estimates (in terms of Btu/bbl of product) for specific processes within the petroleum refining industry were obtained from Oil and Gas Journal information (33). Production data (32) for the various processes were reported by Gordian and multiplied by the energy consumption estimates to yield steam, electrical, and direct-fired energy consumption data.

The estimates are based upon 1973 production data and quantify only energy consumption by processes within the petroleum refining industry, since this 4-digit industry consumes approximately 95% of the fuel purchased by SIC 29. In addition, this industry is characterized by heavy reliance on direct firing; therefore, analysis of only this industry within SIC 29 was deemed consistent with the objective of this study.

2.2.5 Stone/Clay/Glass

In general, process energy requirements for the stone/clay/glass industry group were obtained from Battelle (8,25,26) and Bureau of Mines (27,28) information. However, the cement industry's energy consumption estimates were based on Conference Board data (6). Process energy requirements were obtained by multiplying specific energy consumption values (in terms of Btu/ton of product) by annual production tonnages. The energy is allocated to electrical and direct-fired users.

Energy consumption totals for the mineral processing industries are based primarily upon 1975 production levels, although the cement industry's energy requirements reflect 1979 production conditions. Several of the industries' energy consumption estimates are based upon 1973 production data.

The "process" energy accounted for includes pollution control energy, where such information is available. However, energy for mining, transportation, lighting, product handling, HVAC systems, etc., is not included.

2.2.6 Primary Metals

In general, energy consumption data for the primary metals industry group were obtained by multiplying Battelle's specific process energy values (in terms of Btu/ton of product) by annual production tonnages. American Iron and Steel Institute data (7) and Dow energy estimates (44) were also used in analysis of the complex iron and steel industry. Process energy requirements were assigned to steam, electricity, direct firing, and metallurgical reductant categories. Steam credits were accounted for as "negative" energy consumption, and carbon electrodes were classified as metallurgical reductant.

Most estimates are based upon 1975 production levels and include energy consumption for "process" purposes only.

The iron and steel industry was subdivided into steel castings, gray iron castings, and steel slabs. Values of energy consumption by the iron and steel casting segments were obtained from Battelle energy and production data. Estimates of energy consumption by the steel slab segment were based primarily upon Battelle energy information and AISI production data; information reported by Dow was used in the development of data estimating the amount of energy required in the heat treatment of steel slabs.

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